ELECTROMAGNETIC TRANSIENT SIMULATION WITH STATE VARIABLE REPRESENTATION OF HVDC CONVERSION

By

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ABSTRACT

This thesis describes an accurate and efficient method for transient simulation of HVdc/ac power systems.

An overview of existing transient simulation methods for power systems, with special emphasis on HVdc converter plant, is made, and their main features outlined. The two alternatives in current use, Electromagnetic Transient Programs and State Variable Analysis, are given special consideration. The first method while being efficient and flexible suffers from numerical oscillations when simulating switching components, requiring remedial methods which reduce its effectiveness. The latter method while producing stable and accurate simulation of switching devices, results in inefficient computation for practical ac system sizes.

A hybrid algorithm is proposed which combines the efficiency and flexibility in system representation of the Electromagnetic Transient Simulation programs and the accuracy of the state variable programs to handle HVdc converter non-linearities.

The hybrid method is applied to several test systems and the performances are compared with those of an Electromagnetic Transient program. The proposed method is applicable to any ac/dc power system, with single or multiple non-linearities.

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CONTENTS

ABSTRACT iii

ACKNOWLEDGEMENTS v

LIST OF FIGURES xi

LIST OF SYMBOLS xiii

ABBREVIATIONS xv

Chapter 1 INTRODUCTION 1

1.1 Research in HVdc systems 1

1.2 Requirements of power system analysis 2

1.3 Computer modelling 3

1.3.1 Need for accurate modelling and flexibility 3

1.3.2 HVdc system simulations 4

1.4 Thesis outline 4

Chapter 2 TRANSIENT SIMULATION METHODS FOR HVDC/AC POWER SYSTEMS 7

2.1 Introduction 7

2.2 Transient simulations 7

2.2.1 Terminology 8

2.3 HVdc Simulator 8

2.4 Digital Simulators 9

2.4.1 Digital computers 9

2.4.2 Real-Time Digital Simulator 9

2.5 Transient Simulation Methods for Digital Computers 10

2.6 Dynamic Modelling of HVdc 11

2.7 State Space Formulation 11

2.8 Integration methods used by the state variable programs 14
2.9 Electromagnetic Transient (EMT) programs 15
2.10 The EMTP 15
2.10.1 EMTP formulation 15
2.10.2 Network solution by ordered elimination 17
2.10.3 Network solution with switches 17
2.11 Models available in the EMTP 17
2.11.1 EMTP - TACS Control system modelling 18
2.11.2 EMTP switches 18
2.12 The EMTDC program 19
2.12.1 EMTDC program structure 19
2.12.2 Converter models 20
2.12.3 Control systems 21
2.12.4 Initial conditions 21
2.13 The NETOMAC simulation program 21
2.13.1 HVdc system simulation 22
2.13.2 Initial conditions 22
2.13.3 Network solution scheme 22
2.14 Problems with switching using fixed time step interval 23
2.14.1 Damping the numerical oscillations 23
2.15 Combination of state variable and EMT programs 24
2.15.1 State variable SVC module with EMTDC 25
2.15.2 State variable converter module for EMTP 26
2.16 Conclusion 26

Chapter 3 TRANSIENT CONVERTER SIMULATION (TCS) 29
3.1 Introduction 29
3.2 Structure of TCS 29
3.3 Forming network equations 30
3.3.1 TCS formulation 30
3.4 Numerical solution 33
3.5 Automatic time step adjustment in TCS 33
3.6 Converter models 34
3.7 Monitoring and control of converter operations 34
3.7.1 Valve firing 34
3.7.2 Valve extinctions 34
3.8 Effect of automatic time step adjustments 36
3.9 A possible TCS application to harmonic analysis 39
3.10 Converter controls 40

	3.10.1 TCS converter control	40
	3.11 Implementing a new PLO controller in TCS	41
	3.12 Testing the new firing controller operation	43
	3.13 Conclusion	43
Appendix 3A	**TCS INTEGRATION METHOD**	**46**
Chapter 4	**PROPOSED HYBRID SIMULATION METHOD**	**47**
	4.1 Introduction	47
	4.2 Hybrid approach	47
	4.3 Choice of component modelling	47
	4.4 Component programs in hybrid environment	49
	4.4.1 EMTDC in hybrid environment	49
	4.4.2 TCS in hybrid environment	50
	4.5 Implementation of the Hybrid algorithm	50
	4.5.1 Phase advancing technique	52
	4.5.2 Network tearing and interface	53
	4.5.3 Current compensation	54
	4.6 Control systems representation	55
	4.7 Computer Implementation of the hybrid method	56
	4.8 Conclusion	60
Chapter 5	**SIMULATION RESULTS**	**61**
	5.1 Introduction	61
	5.2 Initial conditions	62
	5.2.1 Dynamic initial conditions	62
	5.3 Test systems representation	63
	5.4 Steady-State Performances	64
	5.4.1 Hybrid Simulation	64
	5.4.2 EMTDC Simulation	65
	5.5 Transient Performances	71
	5.5.1 Test system 2	71
	5.5.2 Test system 3	79
	5.5.3 Test system 4	83
	5.6 Validation of the Hybrid Solution	91
	5.7 Conclusion	94
Appendix 5A	**TEST SYSTEM 1 DATA**	**95**

Appendix 5B **TEST SYSTEM 2 DATA** **95**

Appendix 5C **TEST SYSTEM 3 DATA** **96**

Appendix 5D **TEST SYSTEM 4 DATA** **96**

Chapter 6 **GENERAL CONCLUSIONS AND FURTHER WORK** **99**

6.1. Conclusions 99

6.2 Further work 100

REFERENCES **103**

LIST OF FIGURES

2.1 Discretization of L,C elements using trapezoidal integration method 16
2.2 EMTDC flow chart 20

3.1 TCS flow chart 31
3.2 Fundamental branch representations in TCS 32
3.3 Interpolation of time upon valve current reversal 35
3.4 NETOMAC simulation responses (Source: Figures 3 and 4 of [Kruger and Thumm 1986a] ©IEEE MONTECH '86) 37
3.5 TCS simulation with 1 ms time step (firing angle 25°) 37
3.6 Steady state responses from TCS (firing angle of 25°) 38
3.7 Transient simulation with TCS; dc short circuit at 0.5 s 38
3.8 Phase Locked Oscillator based firing control mechanism 42
3.9 Synchronizing error in firing pulse (Source: Figure 7.3 of [EMTDC 1988]) 42
3.10 Constant α_{order} operation with a step change 44
3.11 Constant current control with a step change; dc voltage 44
3.12 Constant current control with a step change; dc current and α 45

4.1 Reduction of R,L,C branches to simple equivalent in EMTDC 48
4.2 A three phase single port network interface between EMTDC and TCS 50
4.3 A two port interface between EMTDC and TCS 51
4.4 Timing synchronization 52
4.5 Network subdivision and interface 53
4.6 Current compensation in an interface (Source: Figure 8 of [Gole and Sood 1990] ©1990 IEEE) 54
4.7 Control systems in state variable representation 55
4.8 Control systems representation in EMTDC 56
4.9 Subroutine DSDYN for Hybrid simulation 57
4.10 MAIN TCS simulation loop 58
4.11 Monitoring converter operation and control 59

5.1 Test system 1; back-to-back dc link 64
5.2 Hybrid representation: back-to-back dc link 65
5.3 Test system 1 start up response: Hybrid method 66

5.4 Steady state dc voltage waveforms: Hybrid method 67
5.5 Steady state current waveforms: Hybrid method 68
5.6 Steady state dc voltage waveforms: EMTDC 50 μs 69
5.7 Steady state dc voltage waveforms: EMTDC 10 μs 70
5.8 Test system 2 & 3; point-to-point dc link 71
5.9 Test system 2 start up responses: Hybrid method 72
5.10 Test system 2 response due to a single phase 5 cycles fault at inverter end, Hybrid method 73
5.11 Start up response: EMTDC 50 μs 74
5.12 Start up response: EMTDC 10 μs 75
5.13 Test system 2 response due to a single phase 5 cycles fault at inverter end, EMTDC 40 μs 76
5.14 Test system 2 response due to a single phase 5 cycles fault at inverter end, EMTDC 30 μs 77
5.15 Test system 2 response due to a single phase 5 cycles fault at inverter end, EMTDC 20 μs 78
5.16 Test system 2 response due to a single phase 5 cycles fault at inverter end, EMTDC 10 μs 79
5.17 Control system representation for Test system 2 81
5.18 Test system 3 start up response: Hybrid method 82
5.19 Test system 3 transient response due to a single phase fault at inverter end: Hybrid method 84
5.20 Test system 3 transient response due to a single phase fault at inverter end: Hybrid method 85
5.21 Test system 3 transient response due to a three phase fault at inverter end: Hybrid method 86
5.22 Test system 3 transient response due to a single phase fault at inverter end: EMTDC 87
5.23 Test system 3 transient response due to a single phase fault at inverter end: EMTDC 88
5.24 Test system 3 transient response due to a three phase fault at inverter end: EMTDC 89
5.25 Test system 4; back-to-back dc link with extended ac system 90
5.26 Test system 4 start up response: Hybrid method 91
5.27 Transient response due to a remote fault at Gen_1: Hybrid method 92
5.28 Expanded dc voltage response at mid-point due to a remote fault at Gen_1 93

LIST OF SYMBOLS

$B2$	valve firing pulse synchronization error
C	capacitance
E	emf source voltage vector
G	conductance matrix
I	current vector
$I(t-\Delta t)$	history current vector
I_{dc}	dc current
I_{order}	ordered dc current
K	node branch incidence matrix
L	inductance
P_i	firing pulse to valve i
P_{dc}	dc power
Q	capacitive node charge
R	resistance
RLC	resistance, inductance and capacitance
T_{off}	valve off time
T_{on}	valve on time
V	voltage vector
V_c	converter commutating busbar voltage
V_{dc}	dc voltage
ΔT	fixed time step interval
Δt	variable time step interval
Ψ	inductive branch flux
α	converter delay angle
α_{order}	ordered converter firing angle
$\dot{x}$	time derivative of state vector
γ	extinction angle
γ_{min}	minimum extinction angle
ω	angular frequency
θ	electrical angle
ε	state variable convergence tolerance
ε_d	state variable derivative convergence tolerance

$c(i)$	i^th valve firing ramp
$i(t)$	instantaneous current
$v(t)$	instantaneous voltage
x	state vector
Z	impedance matrix
ac	alternating current
dc	direct current
h	integration step length
t	time

ABBREVIATIONS

B6P110	bipolar 6-pulse converter module (EMTDC)
CCC	constant current control
CEPEL	Centro de Pesquisas de Energia Eletrica (Brazil)
CIGRE	Conference Internationale des Grands Reseaux Electriques a haute tension
CPU	central processor unit of the computer
CSMF	control system modelling function library
DOE	Department of Energy (USA)
DSDYN	digital system dynamics subroutine
DSOUT	digital system output subroutine
EAC	extinction angle control
EFC	equidistant firing control
EMT	electromagnetic transient
EMTDC	electromagnetic transient dc program
EMTP	electromagnetic transient program
EPRI	Electric Power Research Institute
FACTS	flexible ac transmission systems
FGH	Forschungsgemeinschaft Hochspannung-und Hochstromtechnik E.V. (Germany)
G6P110	generic 6-pulse converter module (EMTDC)
G6P200	generic 6-pulse converter module (EMTDC)
HVdc	high voltage direct current
IEE	Institute of Electrical Engineers (UK)
IEEE	Institute of Electrical and Electronic Engineers (USA)
IHA	iterative harmonic analysis
IPC	individual phase control
IREQ	Institut de Recherche d'Hydro-Quebec (Canada)
NETOMAC	network torsion machine control simulation program
PLL	phase locked loop
PLO	phase locked oscillator
RTDS	real time digital simulator
SC	study committee

SVC	static VAr compensator
TACS	transient analysis of control systems
TCR	thyristor controlled reactor
TCS	transient converter simulation program
TNA	transient network analyser
TSC	thyristor switched capacitor
UMIST	University of Manchester, Institute of Science and Technology
VDCOL	voltage dependent current order limiter
Z	impedance matrix
ac	alternating current
dc	direct current
h	integration step length
km	kilometer
ms	millisecond(s)
s	second(s)
t	time

Chapter 1

INTRODUCTION

1.1 Research in HVdc systems

Since the first commercial application in 1954, HVdc Transmission has become an acceptable and competitive technology and is now regularly considered as a possible contender in most projects involving high voltage power transmission.

The basic principles and state of the art technologies have been reported from time to time in books [Adamson and Hingorani, 1960; Kimbark, 1971; Uhlmann, 1975; Arrillaga, 1983a] and papers; the latter being too numerous to list them individually. Regular annotated bibliographies now appear under the auspices of the IEEE working group 15.05.07. The latest volume [Bibliography, 1984-1989] contains about 2000 entries, each with an abstract, and divided into seven subject areas.

The oldest organization coordinating the international efforts on the subject of HVdc is CIGRE, first under study group-10 and more recently SC 14. However, the number of national, international and private organizations interested in the subject are increasing all the time. Among these are:

IEEE (USA)
IEC (Europe)
EPRI (USA)
EPRI (China)
CESI (Italy)
USSR
IREQ (Canada)
CEPEL (Brazil)
Manitoba HVdc Research Center (Canada)
CRIEPJ(Japan)
FGH (Germany)
DOE (USA)

CIGRE SC 14 is now accepted as the main coordinating body and all the other organizations report on their activities at the annual meeting of study committee 14. This ensures a general awareness of the progress made, alerts industry on new ideas and encourages research and development on the topic.

As an indication of present activity the main topics undergoing scrutiny by working groups of study committee 14 are:

- Valves for HVdc
- Control of HVdc systems
- Reactive power compensation and Harmonics
- Distortion limits
- HVdc system performance
- Interactions between ac and dc systems
- Switching equipment
- Unit connected Generator
- Converter transformer reliability and performance
- Upgrading DC systems
- Commissioning of DC systems
- Overvoltages in HVdc cables

Recently both IEEE and CIGRE have established new working groups to consider FACTS, an anagram for Flexible AC Transmission System, which deals with the use of power electronics in ac transmission systems.

1.2 Requirements of power system analysis

Among the alternative forms of energy supply only electrical energy must meet all the requirements of conversion, transmission and distribution on an instantaneous basis (at least until means of bulk power storage become feasible). Increased flexibility and fast controllability requirements have prompted the industry to absorb all the relevant advancements in the field of power electronics. The successful use of point to point HVdc transmission has encouraged consideration of interconnected dc systems in multiterminal operation for improved economy and flexibility. The complexity of HVdc control and protection requires detailed study of the operational problems taking into account the various ac/dc system interactions. Furthermore, prospective applications of power electronic devices are being seriously considered in the form of FACTS devices, thus reiterating the need for advanced tools to assess the viability of such devices and study their behaviour within the power system.

As systems become more and more complex, the digital computer becomes an attractive option providing a very flexible and cost effective tool to perform the required studies. Therefore, an important part in the advancement of the HVdc technology is the subject of computer simulation.

In this respect some of the specific phenomena, like the transient behaviour of the HVdc valve structures, require special software.

In general, however, the HVdc converters and systems are an integral part of the overall power system and their behaviour must be represented in the more traditional power system studies such as power flows, harmonic analysis, system reliability and detailed transient simulation.

In particular time domain simulation, sometimes referred to as dynamic and others transient simulation, is the most active area of current development to ensure realistic modelling of the interaction between ac and HVdc power systems.

1.3 Computer modelling

Most of the working group activities listed in section 1.1 require the use of suitable modelling capabilities for quantitative assessment. Therefore, although the field of computer modelling and system studies does not come directly under the umbrella of CIGRE study committee 14, there is a growing need for liaison and various Joint Task forces are being established to produce modelling techniques that take into account the problems encountered by HVdc experts. Other obvious committees involved in this area are study committees SC 36 (on Interference) and SC 38 (on System studies).

One of the main problems encountered in assessing modelling techniques is the lack of commonality between the system conditions used in different studies. To alleviate this problem CIGRE 14-02, the working group on *Control in HVdc Systems*, has recently produced a benchmark model suitable for the validation of alternative dynamic models [Szechtman *et al.*, 1991].

1.3.1 Need for accurate modelling and flexibility

Power system planners require appropriate tools to take into account new and challenging technological advances in their designs. It is clear that the use of high speed power system control action, such as generator static excitation, HVdc transmission and FACTS controllers, can excite oscillations if improperly designed. Conversely, the same controllers can also be designed to damp oscillations. The reliability of simulation results is of utmost importance for accurate predictions.

No unique tool can provide solutions to every practical problem, and specialized tools have been developed to meet different study requirements as economically as possible, ranging from single phase fundamental load flow solution to detailed dynamic simulations.

Another problem in the modelling area is the computation demands, which often limits unrealistically the size of the system represented or uses reduced equivalent representations. However, these restrictions are easing with the increasing computer capabilities.

Although the incentives to lower the computing overheads in analysis are not now as significant as in earlier periods, the expectation of faster and more realistic solutions have also increased; for instance attempts are being made towards real time digital simulation capable of representing the behaviour of the monitoring and control system as it occurs. With such targets in mind, the need for efficient solution still remains.

An efficient modelling technique should provide simulation economy and flexibility of system representation without restricting solution accuracy.

1.3.2 HVdc system simulations

The individual discretization of the network equivalent circuit components using trapezoidal integration is generally accepted as the most efficient technique in conventional power systems transient simulations [Dommel, 1969]. These are well known as electromagnetic transient programs.

It is therefore understandable that considerable effort is being made to accommodate the presence of power electronics components such as static VAr compensators and HVdc converters within the framework of the trapezoidal discretization technique. However the behaviour of an HVdc link is dominated by unspecifiable switching discontinuities with intervals within the millisecond range and the inaccurate treatment of such discontinuities produces numerical oscillations. As their occurrences do not coincide with the discrete time intervals used by the efficient fixed step trapezoidal technique, the latter is being 'continuously' disrupted and therefore rendered less effective.

State space modelling with the system solved as a set of non-linear differential equations can be used as an alternative to individual component discretization [Arrillaga *et al.*, 1983]. The numerous advantages of the state space method for the simulation of frequently switching elements have been discussed in the literature. This formulation permits the use of variable step length integration, capable of locating the exact instants of switching and hence avoiding the appearance of spurious spikes in the waveforms. Although the state space formulation can handle any topology, the automatic generation of the system matrices and state equations is a complex and time consuming process, which needs to be done every time switching occurs.

1.4 Thesis outline

The main aim of this work is to identify the strength of existing transient simulation methods and programs to try and combine their best features to provide an efficient and accurate simulation method. The approach concentrates on maintaining the component programs in their original form and interconnecting the different models through stable interfaces, to make the approach of more general applicability to any other similar programs.

In chapter 2 a brief review of various transient simulation methods of HVdc/ac systems is given. Major aspects related to dynamic modelling of HVdc converter plants specifically and the problems related to numerical oscillations and remedial damping methods employed are discussed. Existing state variables simulation methods and electromagnetic transient programs are identified, and their main features explained.

In chapter 3 the TCS (Transient Converter Simulation) [Arrillaga *et al.*, 1983], an advanced algorithm based on the state variable method, is given special consideration with particular reference to its strength in modelling switching non-linearities. A more flexible firing controller based on the phase locked oscillator is added to TCS and its performance verified.

Chapter 4 proposes a hybrid algorithm combining the EMTP and state variable methods selecting their best features. The algorithm is designed essentially to be a part of the EMTP family. The well established EMTDC [Woodford *et al.*, 1983] program based on the EMTP formulation is chosen as the main program for its wider availability and programming flexibility. TCS is chosen as the state variable alternative for its accurate simulation of HVdc converter systems.

Chapter 5 applies the proposed algorithm to several test systems and compares its simulation performances with the EMTDC program. Finally, chapter 6 draws the concluding remarks and offers suggestions for further research directions.

Chapter 2

TRANSIENT SIMULATION METHODS FOR HVDC/AC POWER SYSTEMS

2.1 Introduction

Transient simulation is extensively carried out to study the behaviour of ac/dc systems subjected to various fault conditions or to tune the control system parameters for optimum operation of the dc link and hence the rest of the power system. To do this, the HVdc systems designer should have access to advanced simulation tools.

At present, both dc simulators and digital computer programs are extensively being used, though the trend is towards the use of the latter because of its wider availability and lower cost. Digital solutions are very dependent on the numerical performance of the simulation tools and the flexibility in system representation for successful simulation. With improving numerical methods and fast processing computers the digital simulation techniques and their applicability is on the grow. Moreover, improvements in component representation are making the digital computer methods reliable for transient simulation purposes. By exploiting the parallel processing capability with fast digital processors real time digital simulation is becoming a reality, and in this respect the search for faster, accurate and flexible numerical methods continues.

2.2 Transient simulations

Switching operations, faults, lightning surges, and other intended or unintended disturbances cause temporary overvoltages and currents in power systems. The system must withstand these overvoltages with a certain probability, or their effects must be reduced and limited with protective devices and sophisticated control strategies. The simulation of transient phenomena is therefore important for the proper co-ordination of the insulation, as well as for the proper design of protection schemes and control systems. Simulation is also needed in order to avoid further occurrences of such disturbances [Dommel and Meyer, 1974].

The complexity of the dc system and the ac/dc system interactions has necessitated the development of special tools capable of adequate representations. The principal tools are dc simulators (transient network analyzer (TNA)) and digital computers. The dc simulator has long been the most powerful tool for the design of HVdc systems.

While a dc simulator is being a versatile tool for simulating the dynamic performance under various conditions, ranging from fundamental frequency to high frequency, it is costly and less flexible compared to digital simulation [Padiyar and Sachchidanand, 1983]. With the fast advances in digital computer technology, digital computers are playing an increasingly important role. At present, both the dc simulators and digital computers are used, often in a complementary manner, in the design and analysis of HVdc systems [Martensson *et al.*, 1986].

2.2.1 Terminology

The transient phenomena discussed here are restricted to the milliseconds range or a few cycles until the transient condition is cleared. By nature these phenomena are a combination of travelling wave effects on overhead lines and cables, and of oscillations in lumped element circuits of generators, transformers, and other devices. To distinguish these from the electromechanical oscillations of generators in transient stability studies, they are generally called *electromagnetic transients* [Dommel and Meyer, 1974]. As this work does not focus on the aspects of transient stability studies, the term *transient simulations* is used to refer to the above *electromagnetic transient simulations*. The studies are concerned with time-domain, dynamic behaviour of ac/dc systems, therefore, the terms *time-domain simulation* or *dynamic simulation* are used as alternative terms to refer to the subject under consideration. Also, the terms *state space formulation* and *state variable method* are used interchangeably.

2.3 HVdc Simulator

HVdc manufacturers and large scale utilities have access to HVdc simulators (transient network analyzers) for system studies. The dc simulator is characterized by the scaled physical modelling of all the power circuits associated with an HVdc system while the control circuits can be real. Every component in the system is modelled either by its scaled down physical model or an electronic model. Being a real time model, it is capable of simulating a large number of cases in a short time. Generally, for ease of digital solutions and to save computation time, small signal or large signal models are used for the numerous nonlinear functions to adequately model the dc system for a particular study of interest. Unlike the above, a dc simulator does not need any approximations or simplifications where the same model can cover a wide range of frequencies of interest in real time operation. However, the extent of ac network representation is limited, and the frequency response of the simulator is limited to about that of the switching surges and below. It is possible to minimize the ac network limitation by controlling the voltage sources to exactly match the voltage swings as derived from large system stability simulations by digital computer programs [Martensson *et al.*, 1986], or more accurately by an extensive ac system representation through a digital simulator, with real time capability, interfaced to the dc simulator hardware (see section 2.4.2).

The confidence in the accuracy and validity of dc simulator results have grown due to the fact that all commercial HVdc systems in operation to date have been designed with considerable support from simulator studies.

2.4 Digital Simulators

As opposed to physical modelling of the components, a digital simulator represents the system components analytically by equivalent representations. The most common form is by deriving mathematical equivalents characterizing the behaviour of each component in the system and solving these models to obtain the dynamic behaviour for given conditions.

2.4.1 Digital computers

For a given hardware configuration of a digital computer the solution efficiency depends mainly on the software implementations. Any level of accuracy can be obtained with the correct representation of the models with increased numerical precision. The efficiency, in general, is inversely proportional to the accuracy sought. However, the improved numerical techniques offer methods to estimate and correct the errors which could improve the accuracy and the solution efficiency.

Many software programs have been written for this purpose. The mathematical formulation is based on representing the system with its characteristic differential equations and integrating these over time to give the required responses. This is well suited to studying different system configurations due to the flexible manner in which the power system topology can be set up by software. Greater accuracy is achievable compared to dc simulators, but the optimization of system parameters requires many runs of digital simulation [Watson, 1987]. Wider availability is guaranteed if the digital simulation software is made available on general purpose digital computers. At present, because these computers do not offer the advantages of real-time capability inherent in the dc simulators, this may be expensive in terms of computer time, which is of critical importance to the suppliers of HVdc [Martensson *et al.*, 1986]. In order to solve all the mathematical equations which define a realistic power system model, in say 50 μs steps, calculation speeds of 100's to 1000's of MFLOPS (Millions of Floating Point Operations per Second) would be required. Even the supercomputers would not be able to sustain the required speed of calculation [Wierckx, 1991].

Present day workstations, which can run simulations of any sizeable system within reasonable time limits, are within the reach of power system engineers. This enables many more studies to be performed and various options explored at low cost.

2.4.2 Real-Time Digital Simulator

To overcome the bottleneck of simulation time the need for a cost effective real-time simulator is imperative. This demands high speed processing power of digital computers which are not achievable by the present day general purpose computers. Recent advancements in digital processor technology, coupled with parallel processing techniques and significant software development has led to the realization of a fully digital power system transients simulator capable of real-time operation. The Real-Time Digital Simulator (RTDS), developed by the Manitoba HVDC Research Centre, provides a very powerful tool for the power systems engineer since it combines the benefits of traditional transient network analyzers and software based simulation packages. A more detailed description of the modern RTDS is given by Wierckx (1991).

This facilitates a number of studies to be performed not only on the HVdc systems but also the testing of protective devices. Furthermore, by interfacing with a traditional HVdc simulator the digital simulator can represent an extensive ac network resulting in an economic representation of a large system in hybrid operation. Moreover, it can serve as an excellent tool for training personnel. Many more areas of application will be found as the RTDS gets a wider access to the power system engineers.

Being able to operate in real time, the protective equipment and controllers can be tested, in a simulated realistic environment, by connecting the RTDS through the hardware interface using signal amplifiers. Moreover, the software developments in simulation techniques can be exploited by the RTDS easily.

2.5 Transient Simulation Methods for Digital Computers

Considerable effort has been devoted since the 1960's to simulate the behaviour of ac/dc power systems with digital computers. Various techniques have been developed for transient simulations not only for power systems studies but also for other electrical and electronic networks. With special application to power system networks detailed treatments have been given in the literature [Pender, 1969; Humpage and Wong, 1982; Bickford *et al.*, 1976; Bickford and Heaton, 1986; Greenwood, 1971].

Travelling wave problems are solved traditionally by either Bewley's lattice diagrams or Bergeron's method of characteristics. For computer solutions Bergeron's method was considered to be better suited [Dommel and Meyer, 1974]. **Travelling wave** methods, based on the solution of transmission line equations, have been applied to solution of power networks. Since travelling wave methods are suited towards distributed parameter elements such as lines and cables, lumped parameter elements like generators, transformers etc., are approximated by short stub lines.

The use of **Z-transform** in power system transient has been introduced by Humpage *et al.* (1980). This is based on a multiple node network formulation, resulting in a set of recurrent matrix equations in time domain in which each circuit element has been explicitly included, and from which the electrical quantities can be derived for each node.

For realistic power system studies with ac/dc converters the above two methods have proved rather cumbersome, and hence are not widely used [Watson, 1987].

State space formulation has led to the development of a number of transient simulation models. This approach has shown to be very accurate in representing power electronic components, while the application to a larger power system has proved uneconomic in computer storage and simulation time. With respect to the ac/dc power system the often encountered difficulty is in modelling the power converter, which undergoes frequent switching. These switchings, in general can neither be specified in advance, nor predicted with quasi steady-state models. The total ac/dc system response heavily depends on the operation of these time varying non-linear elements, and hence their accurate representation for ac/dc system simulation is of utmost importance. The converters and the surrounding system must be represented in detail while the rest of the system can be modelled by suitable equivalents. The state space formulation of variable topology systems has been widely treated in the literature and only a brief description is given in section 2.7.

By far the most widely used transient simulation technique is the **electromagnetic transient program** proposed by Dommel (1969), which is based on the Bergerons's method for distributed parameters and the trapezoidal rule of integration for lumped parameters. This effectively transforms every lumped inductor and capacitor to an equivalent resistance in parallel with a current source, thus an entire network with RLC elements reduces to an equivalent network involving only resistances and current sources. The total system solution from a system of differential equations thus reduces to that of a set of simultaneous linear equations, and hence the solution efficiency of this method is far superior to other simulation methods for very large ac power systems. However, for accurate simulations of power converters and frequently switching devices the state space approach has been found more effective [Campos Barros and Rangel, 1985; Gole and Sood, 1990; Mahseredjian *et al.*, 1991].

2.6 Dynamic Modelling of HVdc

Significant improvements in the numerical behaviour of the entire ac/dc system can be achieved by accurate representation of the switching devices such as an HVdc converter or a static VAr compensator (SVC). For this reason model representation of the converters has been given considerable importance. Apart from the switching mechanism a valve firing controller, usually based on the phase locked oscillator [Ainsworth, 1968], is normally built into these HVdc models.

The essential features of modelling an HVdc system are:

1. a method to handle the varying states of the switching devices and updating the network states,

2. deriving the set of differential equations as the system changes states,

3. a solution method, to integrate these differential equations to obtain the dynamic response

4. a control method, to time the switching sequences based on the control orders and the state of the system.

2.7 State Space Formulation

Most electrical network components eg. generators, transformers, filters, transmission lines etc., can be reduced to an RLC equivalent. In the state variable based programs, the individual components of the system are represented by their characteristic differential equations and these are solved using a suitable integration method to obtain the state of the system against time. HVdc converters and SVC's have successfully been modelled using the state space formulation.

However, with the solution efficiency in mind the different state space models for ac/dc systems have undergone significant, sometimes restricting, simplifications aimed at a particular study of interest. Most of the converter simulation methods are based on the solution using a program with many subroutines; each subroutine solving a set of differential equation arising from the particular network topology.

An earlier work on dynamic simulation of HVdc power transmission systems divided the converter operation into several consecutive processes, and the method was referred to as the *central process method* [Hingorani *et al.*, 1966; Hingorani and Hay, 1967].

Hingorani *et al.* (1968) later introduced a problem oriented approach which adopted the topological method of equation formulation resulting in a relatively easy programming, using graph theory and mesh analysis.

The above models, however, were restricted to the representation of the dc converters, with the ac systems defined as infinite busbars, and also the converter model itself had restricted conduction modes in the central process method. Kutta-Merson procedure was used to integrate the resulting differential equations and simplistic controls were used. The converter transformers were represented by their leakage reactances placed in series with the ideal ac system. When required to represent significant ac system impedances and in the presence of ac harmonic filters, these approaches become cumbersome.

The use of Kron's tensor analysis [Kron 1939, 1959, 1963]and diakoptics facilitated the construction of the complete systems of multiconverter stations and associated ac circuitry with ac harmonic filters [Hay and Hingorani, 1970].

O'Regan and Dillon (1970) further emphasized the necessity to represent the ac filters and modelled them as tuned branches and a high pass filter at the converter terminals, but the ac system was represented as an infinite busbar. The system represented lacked flexibility and so was not suitable for realistic simulation purposes. Similarly, other models such as [Peterson *et al.* (1969), Reeve and Kapoor (1971), Htsui and Shepherd (1971) and Smith (1971)] suffered the restrictions of infinite ac system and lack of realistic controls.

To create a more generalized formulation, the necessity for automatic generation of the network equations was realized, and the application of Kron's tensor analysis, made it feasible. Williams and Smith (1973) applied it to the modelling of converter bridges which resulted in an elegant and superior method of dealing with the periodically varying converter topology which was able to assemble and to solve the network equations automatically.

Hitherto the ac system representation with finite impedance and ac filters, and detailed converter controls were not considered simultaneously. The model developed by Giesner and Arrillaga (1971), combined the presence of ac filters and detailed converter controls, which resulted in a realistic representation of a dc link. Thus for the first time a detailed analysis was made possible of the dynamic behaviour of an HVdc system and the influence of the harmonic filters, the influence of different methods of control and the effect of ac system impedance on the operation of the link. This also enabled to study the behaviour of a dc link during the first few cycles following an ac fault, to find how quickly the link could be brought under control and made to operate satisfactorily without resorting to the use of blocking and bypass-valve action.An emf source behind a series/parallel combination of resistance and inductance was used to represent the ac system equivalent [Bowles, 1970]. Three different control systems were applied namely, predictive control (or individual phase control (IPC)), digital control [Arrillaga and Galanos;

1970c]and digital with fault development control [Arrillaga and Galanos, 1969].

Groschupf *et al.* (1973) developed separate programs as building blocks for the essential parts of a power system, eg. an HVdc converter station with filter circuits, control and protection, multiphase line, generator with voltage and prime mover control, and other special programs. Travelling wave theory was used with modal transformation for the representation of the transmission lines. Separate differential equations were generated for the given condition of conducting valves each time a state change takes place. The combined operation of the separate programs depended on the coupling of the results to a single subsystem.

The concept of using tensor analysis and diakoptics introduced by Hay and Hingorani (1970) was also exploited by Williams and Smith (1973). A similar method was adopted by Hamzei-nejad and Ong (1986), while Milias Argitis *et al.* (1978) applied that to a generalized loop impedance matrix formulation using mesh analysis which automatically assembled the differential equations of the system to deal with the periodically varying topology. Submatrices were formed for individual components with passive elements for interlinking to the rest of the system. Then the generalized loop impedance matrix of the interconnected system was assembled from the submatrices corresponding to the converter bridges and the new states introduced by the passive interconnecting elements. Linking the different components required the connections to be decided upon each configuration by introducing new state equations.

Padiyar and Sachchidanand (1983) followed the graph theory approach. Considering 2,3 and 4 valves conducting situations per six pulse bridge, out of the 50 possible states only 39 states were considered on the assumption that the dc link current is continuous. These were handled using three simple cutset matrices which were easily generated. Each component of the system was modelled separately and in a modular fashion which were interconnected using appropriate interface variables. The dynamics of converter controls were modelled in detail and the state equations were solved using a modified Euler method. However, only the limited number of models available could be used and further extension to the program for a detailed representation required extensive programming.

El Serafi and Shehata (1976) described the converter operation by a group of differential equations with cyclically varying subscripts. The dynamics of the alternating voltage, all the current harmonics and the synchronous machine dynamic performance were taken into consideration. However, only 2 or 3 valves conduction modes per bridge were considered. At the inverter end a simplified dc voltage equivalent was used with the dc line represented as a series impedance.

Mudaliar and Chandrasekharaiah, (1985a, 1985b) modelled the converter under normal operation by forming equivalent circuits for each mode of operation and solving for voltages and currents in a cyclic way. A subroutine approach was used to simulate the abnormal conditions until the normal conditions are reached. This required a knowledge of the switching behaviour to assess the incoming conduction pattern from the previous states. The sequential assignment of the various transitions were pre-programmed. Each abnormal process was handled through a separate subroutine. The interconnections of the rest of the system was carried out at the end of one step, which is typically 0.1 ms (1.8^o at 50 Hz).

Lygdis *et al.* (1987) and Giannakopoulos *et al.* (1988b) used a modular modelling technique in conjunction with a modified state-variable approach, to formulate the state equations of various components and solved them separately. A *component connection method* facilitated the use of separate formulation of each power system component with fictitious sources at their terminals. These source values, which are used to interconnect the different components, were calculated by a general algebraic connection equation.

The most significant state variable program development, as far as the present work is concerned, is that of TCS (Transient Converter Simulation) and is described in chapter 3.

2.8 Integration methods used by the state variable programs

The principal aim in choosing a numerical integration procedure is to obtain an accurate, stable and efficient computer solution. Of the different procedures available, multistep methods are not considered appropriate, owing to the many restarting operations caused by the frequent topological changes, and iterative methods are extremely complex, with systems of equations. A one step method, therefore, was considered most appropriate [Williams and Smith, 1973].

The step-by-step Runge-Kutta method is very suitable for equations which contain many discontinuities because each step is computed independently. As the solution cannot be performed through a discontinuity, the problem is overcome by computing up to the point of discontinuity and then restarting from the discontinuity with the appropriate changes in the system differential equations. A variable step length subroutine Kutta-Merson has been employed which automatically subdivides the specified step length to achieve the required truncation error; the original step length must be selected sufficiently small for the maximum frequency considered [Hay and Hingorani, 1970].

The Merson type method estimates the local truncation error at each point. The basis of this method being the assumption that the problem is sufficiently linear around the operating point. It is however, unreliable for highly non-linear problems. The Merson procedure uses five evaluations of the characteristic function, while the standard Runge-Kutta method needs four evaluations.

The fourth order Runge-Kutta method was used by Reeve and Kapoor (1971), Mudaliar and Chandrasekharaiah (1985a), El Serafi and Shehata (1976), and O'Regan and Dillon (1970), while Hingorani *et al.*, (1966, 1968), Hingorani and Hay, (1967, 1970), and Htsui and Shepherd (1971) used the Kutta-Merson procedure.

A modified version of the first difference approximation (rectangular rule of integration) method was used by Smith (1971). The modified Euler method was opted by Padiyar and Sachchidanand (1983), while Giesner and Arrillaga (1971), and Hamzei-nejad and Ong (1986) used the trapezoidal method which has good numerical stability. An implicit trapezoidal integration method was used in TCS [Watson, 1987], which has shown good stability, accuracy and simplicity [Arrillaga *et al.*, 1983]. A description of the TCS integration procedure is given in Appendix 3A.

2.9 Electromagnetic Transient (EMT) programs

The EMT programs based on the method proposed by Dommel (1969) have been universally accepted as general purpose electromagnetic transient simulation programs. Among the many contributions in this area three merit special consideration, ie. EMTP, EMTDC and NETOMAC. The EMTP program was used for ac transmission systems originally and later extended for ac/dc system applications. The EMTDC was specifically designed for the simulation of dc systems with the associated ac systems modelled as in EMTP, while NETOMAC was developed as a collection of programs covering a wide range of frequencies with respect to ac/dc system studies.

2.10 The EMTP

The general purpose digital program EMTP [Dommel, 1969], designed for the simulation of transient phenomena in single and multiphase networks, is capable of handling very large networks efficiently. Originally ac transmission systems were simulated where very little switching or topological changes take place. With the increasing number of HVdc systems the modelling of fast switching components was introduced subsequently. As many electromagnetic transients problems are stiff (ie. the system has a wider spread of eigenvalues) the good numerical stability of the trapezoidal integration method has proved invaluable.

2.10.1 EMTP formulation

A nodal analysis approach is used, as the basis for the formulation of EMTP, which facilitates an elegant interconnection of plant components and modular program development. The node voltages are therefore used as state variables and the branch currents of each component are expressed as functions of the node voltages [Dommel, 1986]. For a branch connected between nodes k and m these are expressed as:

for a resistance R

$$i_{km}(t) = \frac{v_k(t) - v_m(t)}{R}, \tag{2.1}$$

for an inductance L

$$i_{km}(t) = \frac{[v_k(t) - v_m(t)]\Delta t}{2L} + I_{km}(t - \Delta t), \tag{2.2}$$

and for a capacitance C

$$i_{km}(t) = \frac{[v_k(t) - v_m(t)]2C}{\Delta t} + I_{km}(t - \Delta t). \tag{2.3}$$

Similarly, for a transmission line applying the Bergeron's method of characteristics the currents can be expressed as:

from node k to m

$$i_{km}(t) = \frac{v_k(t)}{Z} + I_k(t - \tau) \tag{2.4}$$

and from node m to k

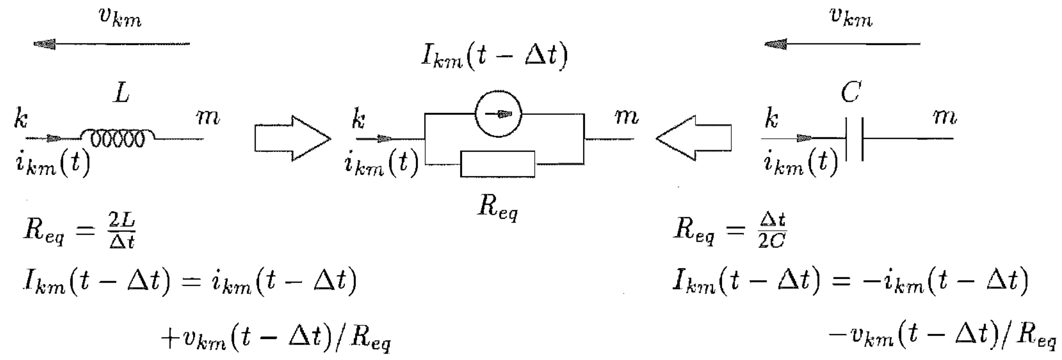


Figure 2.1 Discretization of L,C elements using trapezoidal integration method

$$i_{mk}(t) = \frac{v_m(t)}{Z} + I_m(t - \tau) \tag{2.5}$$

where, $I_{km}(t - \Delta t)$'s are the history terms calculated from the previous integration interval, $I_k(t - \tau)$ and $I_m(t - \tau)$ are the values calculated at time $t - \tau$ (τ is the travel time), and Z is the line surge impedance. Detailed descriptions, of the formulation for transmission lines and deriving equivalents, are given in references [Dommel, (1969, 1974)].

Equations (2.2) and (2.3) indicate that L and C can be represented by an impedance of $\frac{2L}{\Delta t}$ and $\frac{\Delta t}{2C}$ respectively in parallel with the current source $I_{km}(t - \Delta t)$ as shown in Figure 2.1. Hence the total power network can be reduced to one containing resistances and current sources. For any type of network, consisting of these components, with n nodes a system of network equations can be formed as,

$$[G]\,[v(t)] = [i(t)] - [I(t - \Delta t)] \tag{2.6}$$

with,

$[G]$ = $n \times n$ symmetric nodal conductance matrix
$[v(t)]$ = vector of n node voltages
$[i(t)]$ = vector of n current sources
$[I(t - \Delta t)]$ = vector of n known *history* terms

If there are a and b nodes $(a + b = n)$ with known and unknown voltages respectively, Eq. (2.6) can be partitioned into a set A with a nodes and set B with b nodes as shown in Eq. (2.7).

$$\begin{pmatrix} [G_{AA}] & [G_{AB}] \\ [G_{BA}] & [G_{BB}] \end{pmatrix} \begin{pmatrix} [v_A(t)] \\ [v_B(t)] \end{pmatrix} = \begin{pmatrix} [i_A(t)] \\ [i_B(t)] \end{pmatrix} - \begin{pmatrix} [I_A(t)] \\ [I_B(t)] \end{pmatrix} \tag{2.7}$$

The unknown voltages are then solved by,

$$[G_{AA}]\,[v_A(t)] = [i_A(t)] - [I_A(t - \Delta t)] - [G_{AB}][v_B(t)] \tag{2.8}$$

where, $[G_{AA}]$ and $[G_{AB}]$ are built, and $[G_{AA}]$ is triangularized with ordered elimination exploiting its sparsity. From known history terms and known voltages the right hand side of Eq. (2.8) is assembled. This results in a set of simultaneous equations in the form of $[G][v] = [I]$. This system of linear equations are then solved for $v_A(t)$, using the information contained in the triangularized conductance matrix.

2.10.2 Network solution by ordered elimination

As most of the power systems are sparse, a considerable amount of savings in space and CPU time can be achieved in the solution to the final system equations of the form $[G][v] = [I]$. A variation of the *Gauss elimination* method is used, exploiting the sparsity [Tinney and Walker, 1967] of the network matrix, in conjunction with a sparse storage scheme. EMTP uses a *row-by-row elimination method with static storage* [Dommel, 1986]. A node number reordering scheme is applied to reduce the number of fill-in terms. A simple way to get a good ordering scheme is by numbering nodes with only one branch connected first, then ordering nodes with only two branches, and so on.

Repetitive solutions of $[G][v] = [I]$ are needed during transient simulations, either with a change in switching states or more often with changes in $[I]$ only with the same $[G]$ matrix. Therefore, significant savings can be achieved, if the elimination process were split into two parts, one *for the matrix* and the other for a *repeat solution* only. As long as the network structure does not change, only a repeat solution is needed. In this case, the number of algebraic operations is much less than for a complete solution involving the process for the complete matrix, the savings improving with the exploitation of sparsity.

2.10.3 Network solution with switches

The switches are represented as ideal switches or as varying resistances with a large and a small R values used for open and close conditions. When the branch resistance is used for the simulation of the switches, the branch currents can easily be calculated from their node voltages, while for the ideal switches the conducting current is not explicitly available. In order to solve the network for currents within the ideal switches a *compensation method* [Dommel, 1986] is used. The EMTP rebuilds and retriangularises the complete conductance matrix $[G]$ every time a switch state changes.

By ordering the node numbers connected to switching branches last, a partial triangularization of the main matrix is possible. This can be useful when only very few switches and infrequent switching operations are involved. Increased switching operations render this method very inefficient.

2.11 Models available in the EMTP

The EMTP program is modularised with models for various physical components contained in functional modules. These modules include, among others, transformers, transmission lines, switches, surge arresters, control systems and electric machinery [Lauw, 1985]. In general, EMTP is designed to solve any network which consists of interconnections of resistance, capacitance, inductance, single and multiphase π circuits, distributed transmission lines, and certain other elements [Dommel, 1986].

Models of transmission lines and transformers have improved substantially throughout the years. Accurate models were developed to model the distortion of waveforms in transmission lines and saturation in transformers. The program contains a model for a built-in synchronous machine with its mechanical system as well as universal machine models [Lauw and Meyer, 1982] allowing studies for twelve different types of machines. The mechanical behaviour of the machine is modelled as a lumped RLC electric network for the mass-shaft system to which the electromagnetic machine torque appears as a current source.

EMTP provides models for other linear and nonlinear power system components; the simulation of power converters and control systems are discussed in some detail in sections 2.11.1 and 2.11.2. EMTP also provides a range of additional features such as, a power flow calculator, a Fourier analysis program, a *frequency scan* program to derive frequency dependent impedances of a network by current injections, etc.

2.11.1 EMTP - TACS Control system modelling

Transient analysis of control systems (TACS) is a subprogam added to the EMTP by Dube' (1977) for the simulation of HVdc converter controls, and was extended for wider applications of other control systems and modelling special devices or phenomena which cannot be modelled directly with the existing network components in the basic EMTP.

TACS is used to model control systems with the use of transfer function blocks, signal sources, switches, metering and other special devices for proper control system representation. From the network solution TACS accepts network voltage and current sources, node voltages, switch currents, status of switches, and certain internal variables, while the network solution accepts output signals from TACS as controlled sources and as commands to open or close TACS controlled switches.

A Δt step delay is inherent when the electric network and TACS are solved sequentially. Recently, to improve the control system flexibility and to ease the task of modelling digital controls, an EMTP-TACS-FORTRAN interface has been proposed, which claims to introduce no interfacing errors [Bui *et al.*, 1991].

2.11.2 EMTP switches

There are five basic types of switches available through TACS namely, a time-controlled switch a gap switch, a diode switch, a thyristor switch, and a measuring switch. The diode switch closes with a positive forward voltage and stops conducting if the current reduces to less than a specified current margin. Thyristor switch serves as the basic building block for HVdc converters. It is similar to the diode switch except for the firing pulse required for closing the thyristor switch.

Other switch types exist which are specifically designed for statistical overvoltage studies. EMTP provides means for multiple runs with some parameter variations, for example, the time delay between switch openings and closing can be systematically incremented or randomly varied with a given distribution during these runs.

2.12 The EMTDC program

The EMTDC program, specifically designed for HVdc system studies, also has the ability to run detailed ac systems and control system dynamics either individually or in combined operation. Any conceivable electromagnetic and electromechanical system can be easily built with the available program modules or custom built in a user friendly environment. Its flexibility has been maintained by allowing the user developed FORTRAN models to be interfaced easily with an electromagnetic transient solution. A comprehensive explanation of the EMTDC program can be found in the literature [Woodford *et al.*, (1983, 1985), Gole *et al.*, 1984, Irwin and Woodford, 1991].

2.12.1 EMTDC program structure

As a general purpose transient simulation program EMTDC has the following features :

i. The main program solves the electromagnetic transients for the network under study and calls the two user written subroutines. In the first subroutine (DSDYN) the system modules are assembled and all the simulation dynamic informations are specified. In the second subroutine (DSOUT) the required output information is specified.

ii. Disconnected subnetworks (subsystems) are used to minimize matrix size and maximize speed of solution.

iii. Subroutine models of circuit breakers, controls, saturation, surge arresters, rotating machines, power electronic components and modules, control and protection systems are provided in the library for easy assembly.

The main program flow chart is given in Figure 2.2. A single simulation case may be run and outputs observed, or the program can automatically sequence many cases. The multiple run feature enables optimization searches for one or more control variables. A snapshot can be stored for further processing at any required time point of simulation.

Many new features have been added to the EMTDC recently. The technique proposed by Tinney and Walker (1967) is used for the solution of the system equations. Although the sparsity is not exploited, unlike in the above reference a simplified version of the solution method is used which maintains the conductance matrix in its full form. This eliminates the reindexing scheme necessary for sparsity storage and hence speeds up the solution, at the expense of memory. The previous direct inversion of the matrix is thus replaced by retriangularization. By optimally ordering the node numbers partial triangularization of the main matrix is made possible after switching operations. An improved switching algorithm is provided which minimises the risk of numerical oscillations by interpolating to the point of switching. Also a chatter detection and removal algorithm using half time step integration procedure is included to avoid chatter in node voltages and branch currents. With the main EMTDC program an option is available for a very sophisticated user interface to enhance the man-machine interaction.

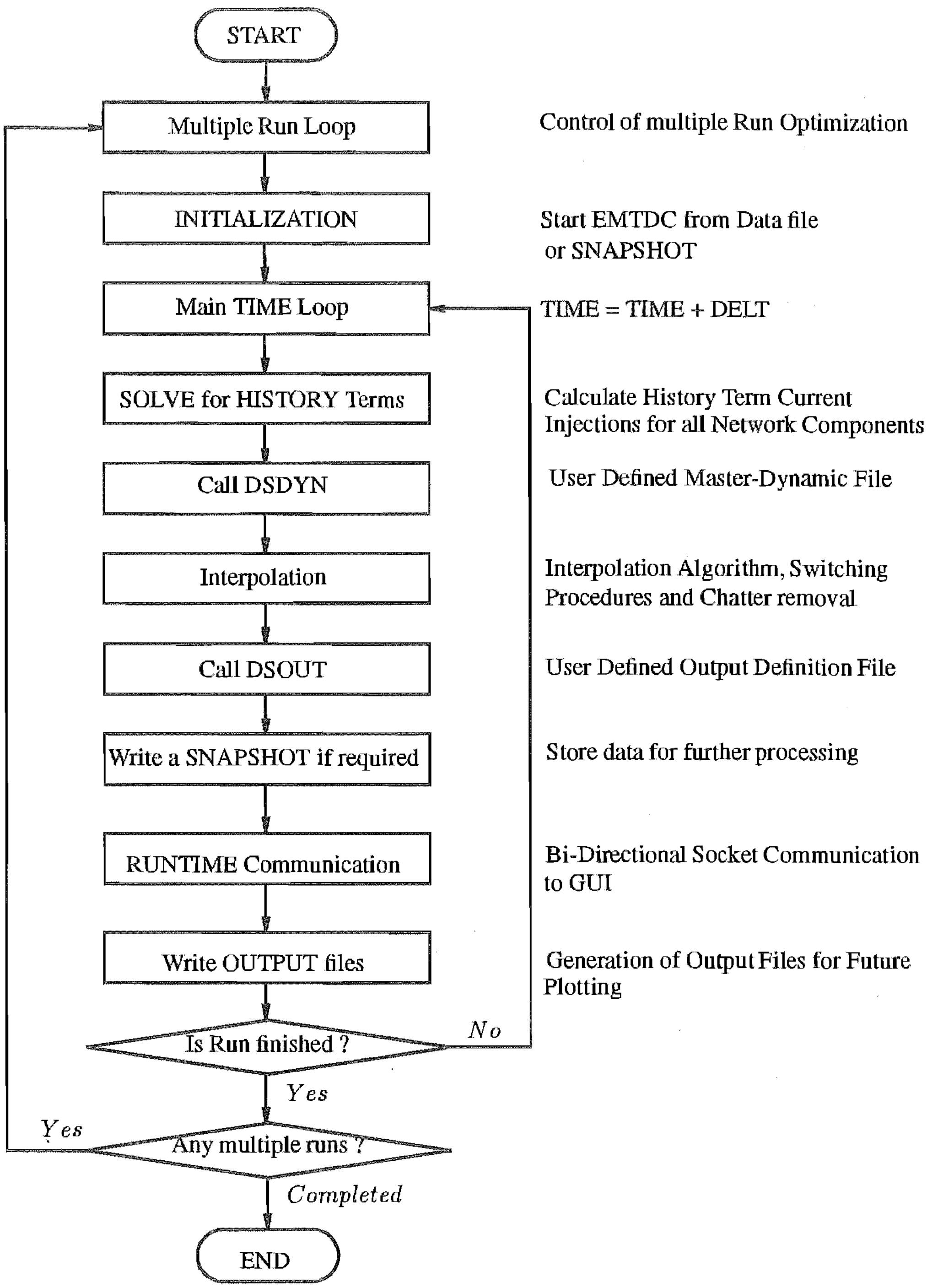


Figure 2.2 EMTDC flow chart

2.12.2 Converter models

Three basic HVdc converter modules are available for 6-pulse, 3-phase Graetz bridges as basic building blocks namely, B6P110, G6P110 and G6P200. The first two use the same firing control system based on the phase locked oscillator. The module B6P110 represents a complete 6-pulse bridge with the dc and ac side interfaced as voltage and current sources respectively. The module G6P110 represents the phase locked oscillator with the associated thyristor switching functions, while the converter transformer and the valves are built as part of the electric power network.

The recent additions to the EMTDC include a converter G6P200 module based on an improved thyristor switch model. This uses a transvektor type PLL [Gole and Sood, 1990] in its firing control system and an improved algorithm with the interpolated time for switching.

2.12.3 Control systems

Control system blocks are available in a modular form to be assembled as sequential blocks, through the continuous system modelling function (CSMF) library. Generic controllers are preprogrammed and modularised. All the blocks are generally solved sequentially as they are called and hence Δt time step delays will be introduced into the control systems. However, for time steps of the order of 50 μs these are considered negligible compared to the control system time constants. It is also possible to run a simulation with only control system blocks without the associated electric power network for dedicated control system studies.

2.12.4 Initial conditions

Initialization, at present, is done by running the simulation for a few cycles to steady-state as a universal steady-state solution to the ac/dc system is not available. Since the EMTDC program permits the inclusion of non-standard user defined dynamic models, which also should be taken into account in such an initialization, it is difficult to provide a general solution. However, the program is flexible enough to employ different strategies to startup a system to steady-state, for example, a dc link can be started from its blocked state gradually.

2.13 The NETOMAC simulation program

Based on the EMTP technique, NETOMAC is a system of digital programs designed to study the electrical power system for electromechanical and electromagnetic behaviour. This includes a wide range of studies in the time and frequency domains. A complete model valid over a wide range of frequencies is computationally uneconomical; instead a set of programs each valid for a frequency range of interest have been combined into what is called the 'program system NETOMAC' [Bayer *et al.*, 1987]. Although not widely available these have been used by HVdc manufacturers for quite some time [Kulicke, 1981].

Two different modes can be selected for the calculation of transient behaviour involving HVdc systems [Kruger and Thumm, 1986b]. Dynamic simulation of converter networks is carried out using the *instantaneous mode*. The *stability mode* (rms value mode) permits transient stability studies by the use of a fundamental frequency quasi steady state model. Both these cases can use the same data records containing information on three phase ac networks and closed loop controls. A special feature of the program when carrying out studies on ac networks is its ability to switch over between the instantaneous and stability modes during the calculation.

As well as fixed frequency voltage sources, synchronous and asynchronous generators can be modelled using Park's differential equations with main field saturation represented. Voltage and turbine control systems can also be used with each synchronous machine. Passive network elements such as linear and nonlinear inductances and resistances, capacitances, lines as π sections or distributed parameter models, and transformers with saturation included are available. A four-terminal network provides isolation between the potentials of the high-voltage and low-voltage sides similar to the real transformers and permits the implementation of phase displacement in three phase transformers.

Control systems for synchronous machines excitation or turbine control can be modelled using a block oriented simulation language. A limited number of blocks are available in the *block library* to build up a closed loop or open loop control system.

Snapshots can be stored at the end of each run and interpreted as the initial conditions for a subsequent run.

2.13.1 HVdc system simulation

The dc circuit can represent thyristor valves with snubber circuit, smoothing reactor, dc filter, and dc line model, while the associated ac network can be assembled with three phase components including various filter configurations. The program permits free interconnection of all components. The instantaneous models for thyristor valves are connected as a three phase bridge.

Switching states are simulated by using admittances which suddenly change from very small value to very large value and vice versa. Thus every switching operation requires a new triangular factorization of the system conductance matrix.

HVdc system controls can be modelled including current and extinction angle measurement and control, logic combinations, firing pulse shifting and blocking capabilities. In addition to control system blocks complete functional modules are available to simulate generic controls.

2.13.2 Initial conditions

Initialization of the ac system can be carried out with the load flow solutions. The power flow conditions are calculated using a single phase model for a balanced ac system. A three phase option is also available for an unsymmetrical system. With the HVdc system present the ac system is initialized from the load flow conditions and the dc system is run to steady state starting from blocked converters and deblocking subsequently.

2.13.3 Network solution scheme

NETOMAC also uses the trapezoidal discretization technique as in EMTP. A constant step is by default used for efficient simulation. However, upon encountering a discontinuity the program includes logics to shift the time mesh automatically to coincide with such instant. This shift coupled with corrections in history terms has shown to remove problems of numerical oscillations [Kulicke, 1981]. The time mesh shift scheme is discussed in section 2.14.1.

In order to achieve sufficiently accurate results, 50 μs has been considered necessary for correct reproduction of the valve turn-on and turn-off events. In between the valve transitions it is possible to use a larger step length. The firing and extinction angles are determined by interpolation independently of the size of the time step. Up to 1 ms time step had been used [Kruger and Lasserter, 1986a] for a simplistic ideal system, although only a realistic value around 50 μs could be acceptable for a useful dynamic simulation (see section 3.8).

2.14 Problems with switching using fixed time step interval

Problems exist in simulating a switch using a fixed step width and the trapezoidal integration method.

i. The switching time as ordered by the control system cannot be carried out by the network solution until the end of the Δt step and therefore the switch closing instant does not coincide with the ordered time.

ii. The decision to open the switch upon detecting a current zero will be effective for the next step only. This situation is of more significance than i. above as numerical oscillation will be the result of such a delay leaving the inductive branch with a non-zero current Δi. The residual energy left in the inductor, $\frac{1}{2}L(\Delta i)^2$ is known to cause the numerical oscillations.

iii. Apart from this residual current caused by switching, the trapezoidal integration method itself can introduce a numerical oscillation even if the switching was performed at current zero.

iv. Small and large values of resistance used for the simulation of switches can cause ill-conditioning of the network conductance matrix.

2.14.1 Damping the numerical oscillations

Among the many solutions to the problem of numerical oscillations in EMT programs the most significant one is probably that due to Kulicke (1981) which for the first time recognized the applicability of the half time step backward Euler method upon detecting the discontinuity. The solution concentrated on avoiding the numerical oscillations occurring in the voltage across inductors and current through capacitors. The solution proceeds by interpolating back to the instant of discontinuity and taking a half time step solution merely for re-initialization of history terms at the discontinuity. From that point the conventional trapezoidal integration scheme is restarted.

Alvarado *et al.* (1983) suggested the use of extra damping, by means of a resistance in parallel with an inductor and in series with a capacitor. These additional damping resistances would introduce errors in the actual inductance or capacitance values and increase losses. Therefore a careful selection of damping parameters is needed to achieve a compromise between accuracy and solution stability; the estimate is made on numerical considerations.

Marti and Lin (1989) introduced two half time step integrations using the backward Euler rule in a procedure called the *critical damping adjustment* (CDA). The trapezoidal rule is used continuously without problem at discontinuities, as the same admittance matrix of the trapezoidal method is used for the half time step solution. No interpolation or re-initialization is required and hence the implementation of this scheme to EMTP was considered straight forward and efficient. However, in the presence of power electronic devices with fast switching the CDA procedure will continue to use the less accurate backward Euler method instead of the accurate trapezoidal integration method.

In EMTDC, the chatter in inductor voltage and capacitor currents or other nonlinearities is eliminated by a half time step interpolation process. Whenever a switching operation occurs, a chatter removal flag is set. A polling process tracks the earliest discontinuity and activates the interpolation at such instant. As soon as an uninterrupted half time step is elapsed the flag is removed. Apart from switching networks other node voltages and branch currents also are passed through a chatter detector for possible chatter removal [Irwin and Woodford, 1991].

In solving the switching problems in EMTDC a method is used which maintains the fixed time step grids although the solution is obtained in between steps by interpolation as follows [Personal communication with G. D. Irwin]:

i. All the history terms are determined in the main time step loop, and a full time step is taken which yields the voltages and currents at the end of the time step.

ii. The earliest switching instant is decided by polling all the switching devices.

iii. Then all the voltages and currents are interpolated to this point and the matrix retriangularized with the change in switch states.

iv. The history terms are then recalculated using these voltages and currents, and another full time step is taken to yield the new voltages and currents.

v. The remainder of the switching devices are polled to see if any remaining devices will switch in this same time step. If all switching is completed, a final interpolation is effected which restores time to the original time step grid.

2.15 Combination of state variable and EMT programs

Further attempts to improve the simulation of switching behaviour by EMT programs have currently been made [Gole and Sood, 1990; Mahseredjian *et al.*, 1991]. The first method was inspirational to this work in respect of marrying the state variable solution to EMTDC from which a step further towards finding a more general approach is realized.

State variable modelling has proved successful in simulating the switching devices as seen from the many cases discussed in section 2.7.

2.15.1 State variable SVC module with EMTDC

State variable models for electric machinery have been interfaced to the EMTDC program [Woodford *et al.*, 1983; Gole *et al.*, 1984]. With the aim of improving the numerical performance of switching in a static VAr compensator, a model based on state variable technique was introduced by Gole and Sood (1990). The model was primarily that of a thyristor controlled reactor (TCR) and a thyristor switched capacitor (TSC). A stable interface links this model to the fixed step width EMTDC program.

The TCR elements were connected in delta, with the thyristor switches modelled as changing resistances, and RC snubber circuits connected in parallel with the thyristors. The TSC branches were modelled as capacitors. Regardless of the number of parallel branches in operation at a given time, all capacitors in each phase were represented together as an equivalent single capacitor to reduce the number of state variables to one per phase. This was based on the assumption that the TSC branch is purely capacitive, because the introduction of inductance would have required that each branch be modelled separately; every added branch required 6 extra state variables. Transformer saturation was introduced by means of a flux dependent current source across the transformer windings.

A detailed SVC controller was also implemented. This uses the EMTDC CSMF functions to process the TCR firing angle and the capacitor switching instants, while the firing controller which decides the exact instant of valve firing was embedded in the model.

Since the main EMTDC program uses a fixed step length as in EMTP, the in-between step width thyristor extinction instants were handled by a smaller time step locally in the model whenever required. When the valve current (inductive branch current) changes sign from positive to negative from time t_A to t_B, the resulting voltage spike is avoided by restarting the process from the point t_A with a submultiple step length to closely detect the turn-off instant. A submultiple value of between two and five was recommended.

The state variable equations were formed using graph theory, and were solved using Adam's second order closed formula; the numerical stability of which is identical to that of trapezoidal rule. The method employed does not involve any matrix inversion and three iterations were found sufficient to guarantee a solution to the model.

Interfacing to the main EMTDC program involves an inherent time step delay in information interchange between the SVC model and the main program. In order to avoid the incremental open circuit conditions from the EMTDC side, particularly when the SVC model is connected at the end of inductive branches, a fictitious resistance is introduced in the main program. This technique is discussed further in section 4.5.3.

Although the model has been designed for studies on the system side certain cases that do not affect the circuit topology can be studied, such as line to line short circuits and valve misfires. However, faults such as a secondary side line to ground short circuit cannot be simulated because it would mean a change in circuit topology and a change in the state equations [Gole and Sood, 1990].

2.15.2 State variable converter module for EMTP

A state variable model of a power converter for HVdc systems was interfaced to the EMTP by Mahseredjian *et al.* (1991). This model was created as a separate program module outside the main EMTP network, and to the EMTP it appears as two sets of nonlinear elements, one set for each ac and dc networks. At each step of EMTP the nonlinear element currents, found in the converter module were used to calculate the values of all EMTP network node voltages, by applying the *post compensation method* [Alsac *et al.*, 1983]. For this the ac and dc networks should be assembled in EMTP.

The converter transformer included within the module, was represented as an ideal two winding transformer with the leakage impedance in series, allowing different transformer configurations. A nonlinear current source modelled the saturation. Thyristor valve switches were represented as ideal switches with an option to include numerical damper circuits in parallel. The control scheme used is based on the digital control scheme of [Arrillaga and Baldwin, 1974], but also is capable of receiving control signals from TACS.

The resulting nonlinear branches from the model were interfaced to the linear network by the post compensation method. A hybrid matrix formulation was necessary to permit the compensation method to be extended for modelling nonlinear voltage sources.

A current discontinuity (an abrupt change of current derivative, caused by valve commutation, for example) in the converter module will start oscillations in the module itself and in the EMTP, when injected through the interface. Applying the Gear-2 [Gear, 1971] method locally with its self damping property, did not eliminate oscillations in the EMTP (where the trapezoidal method was used), which get reinjected back into the module at the next step following discontinuity.

Thus a global treatment of nonlinearity was used called the *discontinuity treatment algorithm*, which uses Gear-1 (Backward Euler) method using two half time step integrations to solve the EMTP network and the converter module upon a discontinuity. The performance of this method has shown to be more efficient than the standard EMTP method. However, the simulation performance results were restricted to a 6-pulse bridge and simple ac and dc circuits without the presence of harmonic filters.

2.16 Conclusion

In this chapter the transient simulation methods proposed in the literature have been briefly surveyed and their digital implementations discussed with special emphasis on state variable and other electromagnetic transient programs. The main focus is on the representation of nonlinear switching devices and the numerical performance around switching discontinuities, the HVdc converters in particular.

Dynamic modelling requirements using state space formulation have been identified and various network formulation and numerical solution methods briefed. Of the EMT programs only the EMTP formulation has been considered in detail.

The EMT programs are able to easily construct the network equations and their formulation results in efficient simulation of large power systems. However the problem of numerical oscillations characteristic of fixed step width trapezoidal integration methods renders the EMT programs less effective for the simulation of switching devices and hence the HVdc converter.

Alternatively, state variable methods, with their ability to easily adapt to variable step length operation, provide a possible solution to the numerical problems. These become inefficient as the system representation expands to more than a manageable size of few nodes and branches. Therefore a complete solution with all the details of a real power system is considered uneconomical.

Deviating from the single method of solution, the idea of marrying the state variable solutions to the EMT programs have been attempted exploiting the strength of the state variable modelling for power electronic devices. However, these were restricted to a single network component separated from the main network. If more than one unit is needed these are modelled independent from each other.

An approach of general applicability which exploits the best features of the state variable methods and EMT programs will be discussed in chapter 4 with its implementation.

Chapter 3

TRANSIENT CONVERTER SIMULATION (TCS)

3.1 Introduction

A nodal approach provides an ideal environment for the analysis of individually modelled components, which are interconnected at their terminals. Nodal analysis with diakoptical segregation of the plant components undergoing frequent switching, to avoid involving the whole network in unnecessary topological changes, was the basis for TCS which started at UMIST and continued at the University of Canterbury [Arrillaga *et al.*, 1983]. The use of diakoptical techniques [Kron, 1963; Brameller *et al.*, 1969] reduces considerably the computational burden. Developments carried out at UMIST included the converter model, the synchronous machine, a coupled coil representation of the converter transformers, transmission lines, harmonic filters and an ac system. The converter controller was based on a direct digital control scheme developed by Arrillaga and Galanos (1970a, 1970b, 1970c), which in principle was similar to the phase locked oscillator of Ainsworth (1968) giving equidistant firing control.

Perhaps the most important addition to TCS carried out at the University of Canterbury was the incorporation of the ac system's time response into the model [Heffernan, 1980]. Further contributions included the use of four different ac system models, a more realistic dc fault representation, transformer saturation and hysteresis effects [Joosten, 1987] and a detailed frequency dependent ac system equivalent model [Watson, 1987]. More recently the control system modelling has been made flexible by using basic building blocks (of control functions); with these the control system of a synchronous machine or an HVdc converter can be built via block oriented data statements [Sankar *et al.*, 1989].

3.2 Structure of TCS

The data input can be very considerable for dynamic analysis representation even for a simple system. Single branch entries and manual formulation of network differential equations is a tedious task in such a case. To make the user input as simple as possible, an automatic procedure to the data input is adopted and the job of expanding the data into the full network is left to the computer.

For each system component, a set of control parameters (composed of four numbers) provides all the information needed by the program to expand the given component data and to convert it to a form required by the program. The component data set contains the initial line current information and other parameters relevant to the particular component. For example, for the converter bridges this includes the initial dc current, delay and extinction angles, time constants for the firing control system, the smoothing reactor, converter transformer data, etc. Each component is then systematically expanded into its elementary r,l,c,s branches and assigned appropriate node numbers as defined in section 3.3.1. A set of cross-referencing information is created relating the system busbars to these node numbers. (Information on these branch and node numbers is also needed for the TCS-EMTDC hybrid interface, discussed in chapter 4). The node voltages and branch currents are initialised to their specified instantaneous phase quantities of busbar voltages and line currents respectively. If the component is a converter, bridge valves are set to their conducting states from knowledge of the ac busbar voltages, the type of converter transformer connection and the set initial delay angle.

The procedure described above, when repeated for all the components of the system, generates the system matrices in compact form with their indexing information, assigns node numbers for branch lists and initialises relevant variables in the system.

Once the system and controller data are assembled the system is ready to begin execution. In the data file, the excitation sources and control constraints are specified followed by the fault specifications. The basic program flow chart is shown in Figure 3.1. For a simulation run the input could be either from the data file or from a previous snapshot (stored at the end of a run).

Simple control systems can be modelled by sequentially assembling the modular building blocks available. Control block primitives are provided for basic arithmetic such as addition, multiplication and division, an integrator, a differentiator, pole-zero blocks, limiters, etc. The responsibility to build a useful continuous control system is left to the user.

At each step of the integration process, converter bridge valves are tested for extinction, voltage crossover, and conditions for firing. If indicated, changes in valve states are made and the control system is activated to adjust the phase of firing. Moreover, when a valve switching occurs, the network equations and the connection matrix are modified to represent the new conditions.

3.3 Forming network equations

Although the state space formulation can handle any topology, the automatic generation of the system matrices and state equations is a complex and time consuming process, which needs to be done every time switching occurs. By restricting the allowable topologies and the application of tensor analysis the automatic generation of system matrices and state equations is made feasible. The fundamental branch representations used in TCS are illustrated in Figure 3.2.

3.3.1 TCS formulation

By defining the capacitive node charge Q and inductive branch flux Ψ as state variables,

$$\Psi_l = L_l I_l \ ; \ \ Q_\alpha = C_\alpha V_\alpha, \tag{3.1}$$

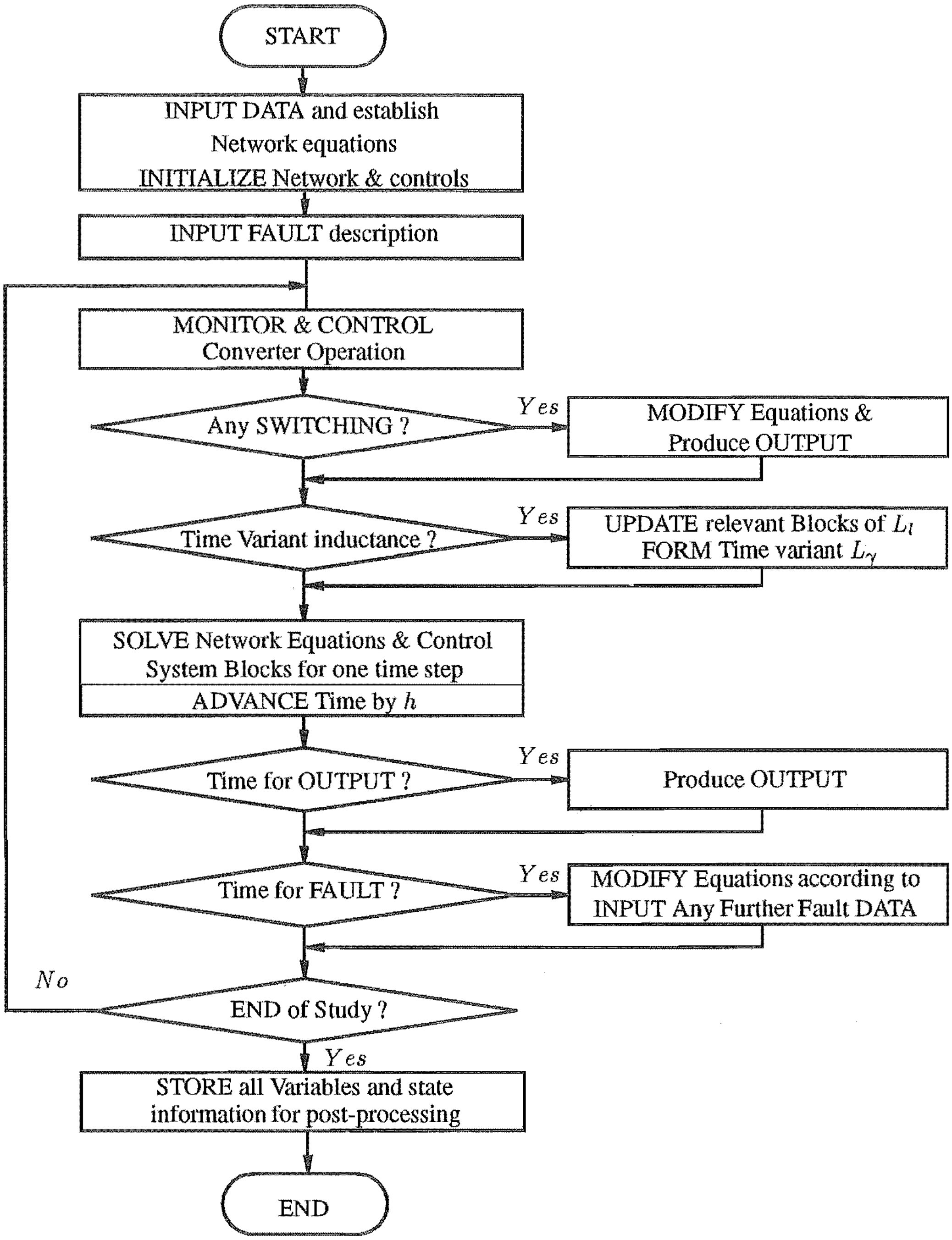


Figure 3.1 TCS flow chart

the vectors V_α and I_l, representing the capacitive node voltage and inductive branch currents respectively, become dependent variables related to the state variables by algebraic relations.

The resulting set of equations can be written as:

State related variables,

$$V_\alpha = C_\alpha^{-1} Q_\alpha \tag{3.2}$$

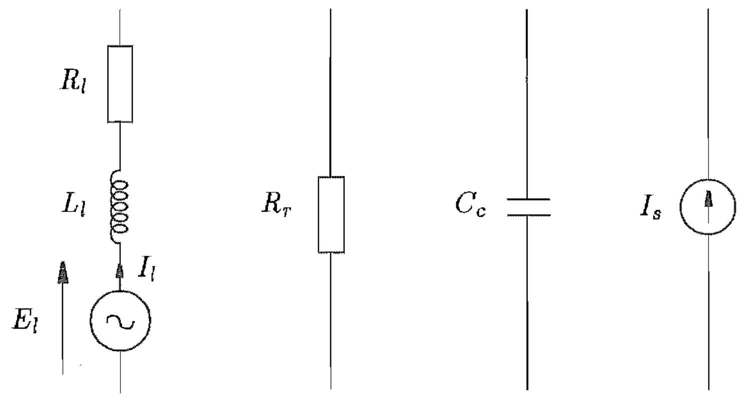


Figure 3.2 Fundamental branch representations in TCS

$$I_l = L_l^{-1}\Psi_l \tag{3.3}$$

Dependent variables,

$$V_\beta = -R_\beta(K_{\beta s}I_s + K_{\beta l}I_l + K_{\beta r}R_r^{-1}K_{r\alpha}^t V_\alpha) \tag{3.4}$$

$$V_\gamma = -L_\gamma K_{\gamma s}pI_s - L_\gamma K_{\gamma l}L_l^{-1}(E_l - pL_lI_l - R_lI_l + K_{l\alpha}^t V_\alpha + K_{l\beta}^t V_\beta) \tag{3.5}$$

$$I_r = R_r^{-1}(K_{r\alpha}^t V_\alpha + K_{r\beta}^t V_\beta) \tag{3.6}$$

and the state equations

$$pQ_\alpha = -(K_{\alpha l}I_l + K_{\alpha r}I_r + K_{\alpha s}I_s) \tag{3.7}$$

$$p\Psi_l = E_l - R_lI_l + K_{l\alpha}^t V_\alpha + K_{l\beta}^t V_\beta + K_{l\gamma}^t V_\gamma \tag{3.8}$$

where,

$$C_\alpha^{-1} = (K_{\alpha c}C_cK_{c\alpha}^t)^{-1} \tag{3.9}$$

$$L_\gamma = (K_{\gamma l}L_l^{-1}K_{l\gamma}^t)^{-1} \tag{3.10}$$

$$R_\beta = (K_{\beta r}R_r^{-1}K_{r\beta}^t)^{-1} \tag{3.11}$$

- E, V and I represent the branch emf source voltage, node voltage and branch current vectors respectively,

- R, L and C are the resistance, inductive reactance and capacitive susceptance matrices respectively. The p operator in TCS represents a derivative w.r.t. electrical angle rather than time.

The rest of the symbols and suffixes in the above equations represent the following:

α = node with at least one capacitive branch connected
β = node with at least one resistive but no capacitive branches connected
γ = node with inductive but no resistive or capacitive branches connected
r, l, c, s = resistive, inductive, capacitive or current source branch

The above definitions give the topological or branch node incidence matrices, their general elements being:

$$
\begin{aligned}
K^t_{pi} &= \;\;\,1 \text{ if node i is the sending end of branch p} \\
&= -1 \text{ if node i is the receiving end of branch p} \\
&= \;\;\,0 \text{ if node i is not connected to branch p}
\end{aligned}
$$

where, $K^t_{r\gamma}$, $K^t_{c\beta}$, $K^t_{c\gamma}$ are null by definition.

Integrating for Q_α and Ψ_l and substituting in the dependent equations the total system solution can be obtained.

Valve ON/OFF states are represented by a short circuit or an open circuit condition and the network topology is changed accordingly. Further details of the TCS formulation for variable topology and component modelling are given in reference [Arrillaga, 1983a]. The current source branch I_s is an addition to the formulation of the above reference [Watson, 1987]. In this work the attention is focused on the converter modelling and simulation.

3.4 Numerical solution

The TCS integration method described in Appendix 3A, uses the implicit trapezoidal integration technique and the solution by this predictor-corrector method has been found sufficiently stable. Other efforts to improve the numerical performance by higher order methods such as by 4^{th} order Runge-Kutta method resulted in poor numerical performance. The problem associated with the Runge-Kutta method is in its sensitivity to imperfect initial conditions [Campos Barros, 1976]. The difficulty of obtaining exact initial conditions for a dynamic analysis from the steady state analysis of a system including harmonic filters, converter transformers, and rotor dampers ruled out the use of this method for such systems. Such problems were not experienced with the trapezoidal algorithm [Heffernan, 1980]. Other multi-step variable step length algorithms [Ralston and Rabinowitz, 1978] are complicated in their implementation and have not been tested.

3.5 Automatic time step adjustment in TCS

The actual computer simulation time is primarily a function of the step length. The optimum step length, with regard to processing time will vary with the system under study; the maximum being governed by the frequency of interest. To ensure fast convergence, the step length is automatically adjusted in TCS. It is increased by 10 % upon fast convergence ($\leq$ 2 iterations) and reducing by 5 % upon poor convergence (> 5 iterations); if the solution fails to converge within 10 iterations the step length is halved and the integration process is restarted at the previous time step [Heffernan, 1980].

3.6 Converter models

TCS provides the basic converter models used in HVdc transmission for 6 or 12 pulse operation, which consist of the converter transformer, the Graetz bridges, and the smoothing reactor as a single unit. The basic units are the 6-pulse bridges, and two units with the transformers phase shifted by 30° provide the 12 pulse configuration. Since the valves are represented as ideal switches, the transformer secondary windings are directly incorporated into the switching process. TCS is built in with the necessary basic mechanism for switching any valve and thus updating the network topology structure. This facilitates any type of valve firing control strategies to be implemented.

3.7 Monitoring and control of converter operations

At each step in the integration process, the converter valve currents are calculated and valves tested for current extinctions. If there were any valve current reversals the respective valves are switched off and the earliest switching instant is used to interpolate back in time. All the dependent variables are calculated at that point in time. Top and bottom valves of an arm of the 6-pulse Graetz bridges are tested for commutation failure. If both valves are conducting a commutation failure flag is set and the corresponding extinction angle counter is reset.

Valve voltages are calculated from the node voltages. Zero crossings of the reference voltages are detected and extinction angles are measured at zero crossings from extinction angle counters which start from the switch off instants. From zero crossing instants the period of the ac system is obtained, filtered and averaged to provide the phase locked oscillator frequency (see section 3.10), from which the equidistant firing pulses are generated for each valve.

3.7.1 Valve firing

When a converter valve satisfies the conditions for conduction, ie. sufficient forward voltage exist with an enabled firing gate pulse, it will be switched to the conduction state. If the valve forward voltage criterion is not satisfied the pulse is retained for a set period without upsetting the following valve.

3.7.2 Valve extinctions

Accurate prediction of valve extinctions is a difficult and expensive task which can degrade the solution efficiency. Sufficient accuracy is achieved by detecting extinctions after they have occurred, as indicated by valve current reversals; by linearly interpolating the step length to the instant of current zero the actual turn-off instant is assessed. Only one valve may be extinguished per bridge at any one time, and the earliest extinction over all the bridges is always chosen for the interpolation process. By defining the current (I) in the outgoing valve at the time of detection (t), when the step length of the previous integration step was h, the instant of extinction t_x will be given by

$$t_x = t - hz$$

where, $z = \frac{I_t}{I_t - I_{t-h}}$

All the variables are then interpolated back to t_x by

$$V_x = V_t - z(V_t - V_{t-h})$$

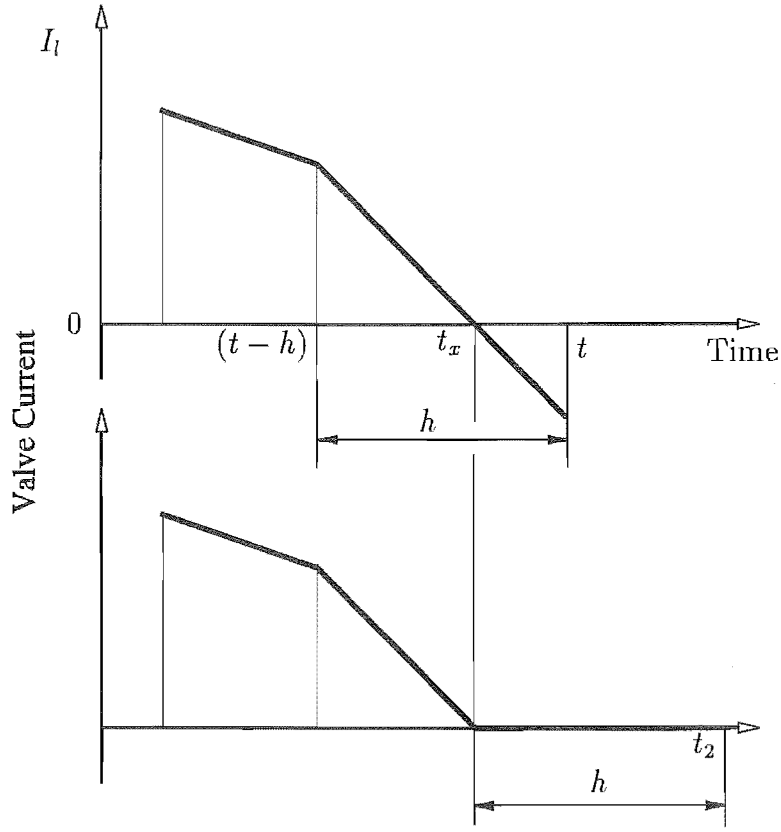


Figure 3.3 Interpolation of time upon valve current reversal

The next integration step will then begin at t_x with step length h. This linear approximation is sufficiently accurate over periods which are generally less than one degree, and is computationally inexpensive. This interpolation process is clearly demonstrated in a case with an extended a 1 ms time step in Figure 3.5.

Caution is exercised when extinguishing a valve since this may produce a non-conducting condition in the converter, ie. the current path is interrupted due to there being no conducting valves in one half of a bridge. Action is taken in such a case to ensure that the valves nearest to the smoothing reactor are 'off' so that the converter side of the smoothing reactor is open circuited, and that the minimum number of valves remain in the conducting state to provide a path within the converter to the common reference point, thus avoiding the need for defining new network nodes [Heffernan, 1980].

Upon switching any of the valves a change in the topology has to be reflected back into the main system network. This is achieved by modifying the connection matrices. When the time to next firing is less than the integration step length the integration time step is reduced to the next closest firing instant. Since it is not possible to integrate through discontinuities, the integration time must coincide with their occurrence. These discontinuities must be detected accurately since they cause abrupt changes in bridge node voltages, and any errors in the instant of the topological changes will cause inexact solutions.

3.8 Effect of automatic time step adjustments

It is important that the switching instants be identified correctly, firstly for accurate simulations and secondly, to avoid any numerical problems associated with such errors. This is a property of the algorithm rather than an inherent feature of the basic formulation. Accurate converter simulation requires the use of a very small time step, where the accuracy is only achieved by correctly reproducing the appropriate discontinuities, although a smaller step length is not necessary away from such events. A smaller step length is not only needed for accurate switching but also for the simulation of other nonlinearities, such as in the case of transformer saturation, around the knee point, to avoid introducing hysteresis due to overstepping [Dommel, 1986]. Also in the saturated region and the linear regions a larger step may be acceptable.

On the other hand, state variable programs and TCS in particular have the facility to easily adapt to a variable step length operation. The dynamic location of a discontinuity will force the step length to change between the maximum and minimum step sizes. The automatic step length adjustment built into the TCS program takes into account most of the influencing factors for correct performance. As well as reducing the step length upon the detection of a discontinuity TCS also reduces the forthcoming step in anticipation of events such as an incoming switch as decided by the firing controller, the time for fault application, closing of a circuit breaker, etc.

To highlight the performance of TCS program in this respect, a comparison is made with an example used by the program NETOMAC (see section 2.13), often quoted as a unique feature of that program [Kruger and Lasserter, 1986a]. The example refers to a test system consisting of an ideal ac system (emf sources) feeding a 6-pulse bridge converter (including the converter transformer and smoothing reactor) terminated by a dc source. The firing angle was fixed at 25^o. Figure 3.4 shows the valve voltages and currents for 50 μs and 1 ms (ie, 1.0 and 21 degrees) time steps respectively. With steps as large as twenty times also the system has settled down to steady state.

The progressive time steps are illustrated by the dots on the curves in Figure 3.4 (b), where interpolation to the instant of a valve current reversal is made and from which a half time step integration is carried out. The next step reverts back to the standard trapezoidal integration until another discontinuity is encountered.

A similar case with ideal ac system terminated with a dc source was simulated using TCS. A maximum time step of 1 ms was used also in this case. Steady state waveforms of valve voltage and current derived with a 1 ms time step, shown in Figure 3.5, illustrate that the accuracy of TCS is better than that of NETOMAC (Figure 3.4 (b)) both in detection of switching discontinuities and reproduction of the 50 μs results. The time step tracing points are indicated by dots on the waveforms.

Further TCS waveforms are shown in Figure 3.6 giving the dc voltage, valve voltage and valve current at 50 μs and 1 ms (although the actual step was modulated under the program's control).

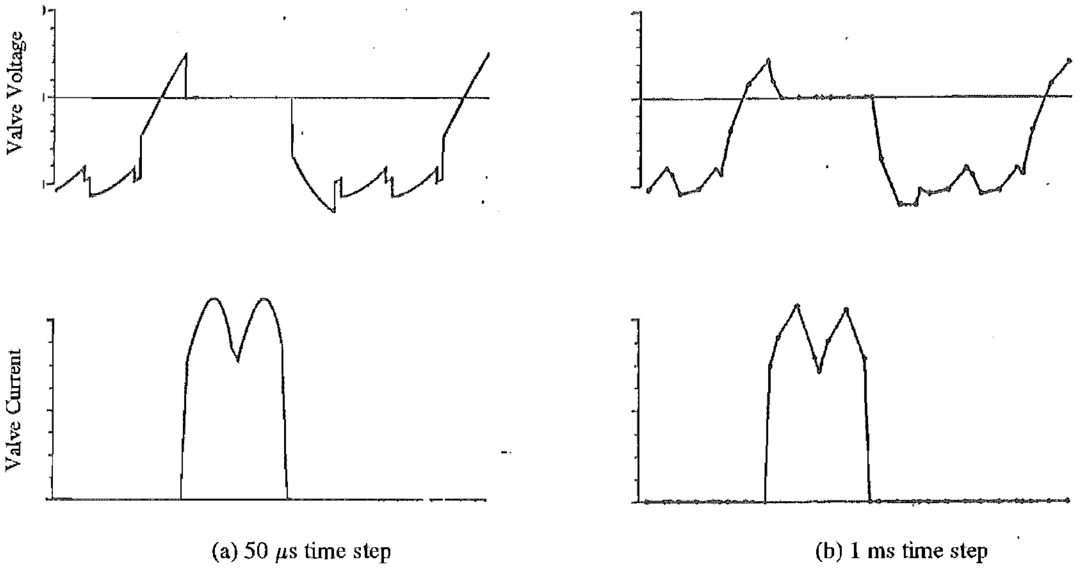


Figure 3.4 NETOMAC simulation responses (Source: Figures 3 and 4 of [Kruger and Thumm 1986a] ©IEEE MONTECH '86)

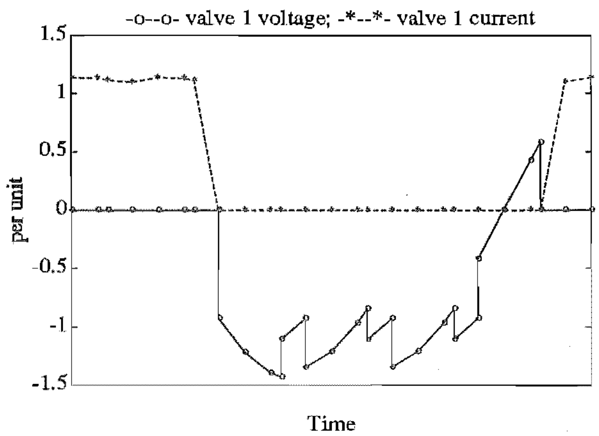
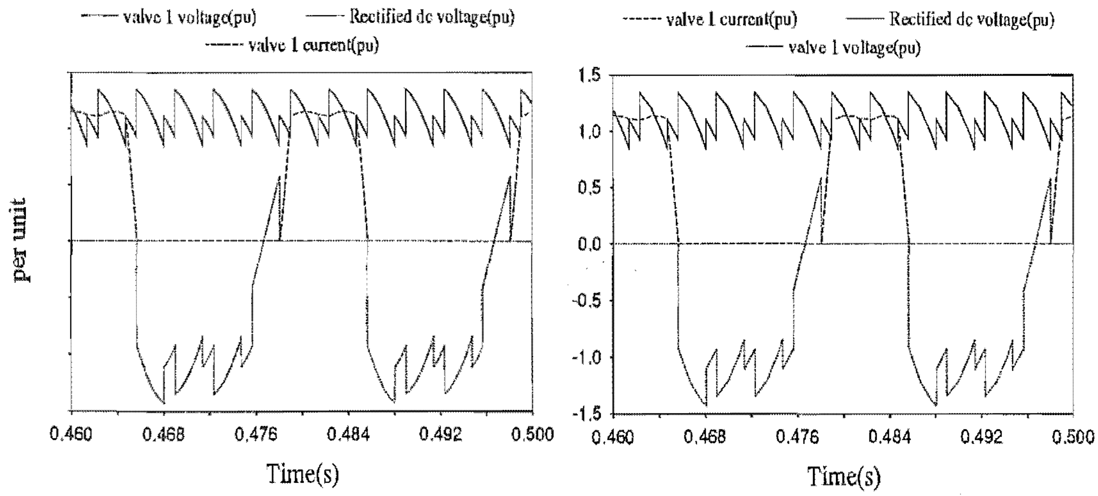


Figure 3.5 TCS simulation with 1 ms time step (firing angle 25°)

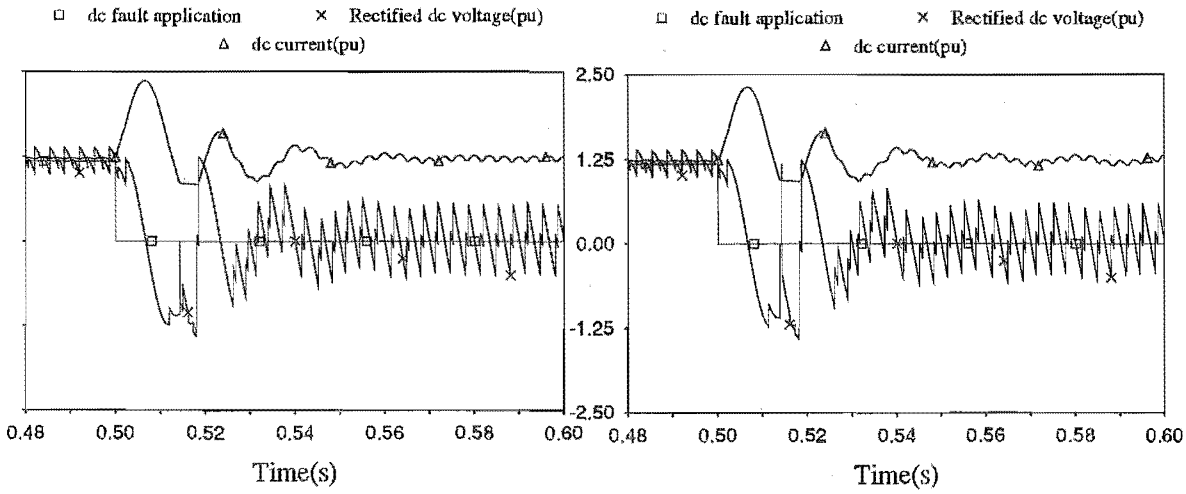
In the NETOMAC case extra interpolation steps are included for the 12 switchings per cycle in the 6-pulse bridge. For the 60 Hz system simulated with 1 ms time step a total of 24 steps per cycle can be seen from the Figure 3.4(b), where a minimum of 16 steps are required. Whereas the TCS cases shown in Figure 3.6 have been simulated with a 50 Hz system. The 50 μs case of Figure 3.6(a) has an average of 573 steps per cycle with the minimum requirement of 400 steps.



(a) 50 μs time step

(b) 1 ms time step

Figure 3.6 Steady state responses from TCS (firing angle of 25°)



(a) 50 μs time step

(b) 1 ms time step

Figure 3.7 Transient simulation with TCS; dc short circuit at 0.5 s

On the other hand the 1 ms time step needed only an average of 25 steps per cycle. The necessary sharp changes in waveshape are derived directly from the valve voltages upon topological changes.

When the TCS frequency is increased to 60 Hz the 50 μs case used fewer steps per cycle, as would be expected, resulting in 418 steps, compared to a minimum required of 333 steps per cycle. For the 1 ms case an average of 24 steps were required as for the NETOMAC case.

The same system was run with a constant current control of 1.225 p.u., and at 0.5 s a dc short circuit was applied. The simulation results with 50 μs and 1 ms step lengths are shown in Figure 3.7. This indicates the ability of the TCS to track the solution and treat waveforms accurately during transient operations (even with such an unusually large time step).

3.9 A possible TCS application to harmonic analysis

The fast solution obtained with a large time step suggests the possibility of using the TCS converter model for steady-state solutions. One possible application is in harmonic power flow assessment as an alternative to IHA (Iterative Harmonic Analysis) [Yacamini and Oliveira, 1980]. Although IHA is essentially a frequency domain technique, the solution requires regular excursions into the time-domain. It is based on the Gauss-Seidel family of iteration techniques, solving the converter and the supply system sequentially. When the solution converges, IHA produces accurate results and is faster than the TCS solution.

The static power converter in IHA is represented by a simplified time domain steady state model, which calculates the ac currents and the dc voltage for the given input conditions (converter bus voltages and dc current). The converter transformer is represented by an ideal transformer in series with its leakage impedance thus ignoring coupling between phases and magnetic saturation characteristics. However, the transformer magnetizing current is a source of harmonics and neglecting it while representing the rest of the system in detail cannot be justified.

The IHA algorithm presents convergence problems when the relative strength of the ac system (determined by the short circuit ratio) is low [Arrillaga *et al.*, 1987]. Moreover, a divergent solution does not indicate a harmonic instability. The convergence problem with IHA is a property of the algorithm and is closely related to the Gauss-Seidel iterative technique used.

Therefore, to improve the iterative solution a Newton type algorithm in the harmonic domain [Acha *et al.*, 1987] must be used. On convergence this iterative process will give the complete solution including the cross coupling between phases as well as harmonics. The need to consider the cross coupling between harmonics has been clearly demonstrated by Medina and Arrillaga (1991). Unlike the IHA, the ac and dc networks can be solved in a unified solution with all the harmonics of interest considered simultaneously. As this process is based on a Newton type algorithm, the numerical performance will be better than the Gauss-Seidel type of iteration techniques.

A complete time-domain solution would be useful for harmonic assessment, if the entire system could be represented with frequency dependency and a facility to obtain a fast steady state solution was made possible.

Instead of a total time domain solution, TCS could be used to provide the steady state solution for the static power converters while the rest of the system consisting of linear and linearized components, could be represented directly in the harmonic domain. The TCS solution should include the converter transformer represented by a coupled coil model and the smoothing reactor explicitly modelled. Unlike IHA, this alternative provides the cross coupling between phases as well as transformer saturation non-linearities.

The combination of TCS and harmonic domain solutions results in an iterative process, which works as follows:

Since the TCS network includes the converter transformer and the smoothing reactor on its ac and dc sides respectively, the converter terminal voltages from the solution of the network in the harmonic domain are used in the TCS solution as voltage sources. The converter network is then solved in the time domain with the given control constraints, such as α, γ, constant current or any other. The resulting periodic 3-phase ac and the dc currents provide the harmonic current injections to the interfacing nodes in the harmonic domain. These currents are used to recalculate the voltage distortions in the harmonic domain. The latter are then used to derive the voltages for the TCS network resulting in an iterative solution.

3.10 Converter controls

The converter firing control plays a very important role in the performance of the HVdc control system. In the early stages of development of HVdc transmission individual phase control (IPC) was used which was found susceptible to harmonic instabilities when firing or voltage unbalances exist [Ainsworth, 1967] or when connected to a weak ac system.

Subsequently an equidistant firing control (EFC) scheme based on a phase locked oscillator was proposed [Ainsworth, 1968]. This method uses a negative feedback in its control loop to adjust the frequency of the phase locked oscillator which generates the firing pulse ramps to maintain the set condition. The advantages of EFC over IPC have been discussed in detail in the literature, eg. [Uhlmann, 1975; Arrillaga, 1983a].

3.10.1 TCS converter control

Present day control schemes are variations of the phase locked oscillator technique developed by Ainsworth. An implementation suitable for digital simulation, proposed by Arrillaga and Galanos (1970a, 1970b, 1970c), has been used in TCS. Although this approach was adequate for most transient simulation cases, the flexibility to model overall control system details was restricted by imbedding the controller dynamics into the converter model itself. Such implementations prevented any further modifications to the preset control principles and only allowed variations to be carried out by the set of control system constants.

Subsequent work by Sankar *et al.* (1989) introduced modular control system blocks of logic, arithmetic and transfer functions, which enables the simulation of feedback type controllers and improves the descriptive representation of the control system.

TCS converter units include a built-in valve firing control mechanism. The converter bridges are modelled as 6-pulse units either in star-star or star-delta transformer configurations.

Valve firing and switchings are handled individually on each 6-pulse unit of a converter. For 12-pulse operation both bridges are synchronized and the firing controllers phase locked loop is updated every 30° compared to the 60° used for the 6-pulse converter.

3.11 Implementing a new PLO controller in TCS

As an alternative to the built-in equidistant firing control proposed by Arrillaga and Galanos, a new control mechanism is incorporated as a part of this work to provide a TCS converter with a firing option according to the strategy used by EMTDC (1988) which is implemented by modifying the basic converter firing control at a lower level in the model. This alternative was particularly useful for the verification of the hybrid implementation (chapter 4) with a different implementation such as EMTDC. Apart from that, the hybrid implementation permits the use of EMTDC CSMF functions for the control system implementation and hence the converter operation of the hybrid and EMTDC models can be made identical down to the level of valve firing. Recently, a converter firing control system based on a transvektor type phase locked loop has been introduced into EMTDC, which has shown superior immunity from disturbances and harmonic distortion on the commutation voltage [Gole *et al.*, 1989]. Although not yet implemented, it is also possible to incorporate similar control strategies into the TCS converter module in a similar way to the firing control implemented.

The firing control mechanism implemented is equally applicable to 6 or 12 pulse valve groups; in both cases the reference voltages are obtained from the converter commutating bus voltages. When directly referencing to the commutating bus voltages any distortion in the bus voltage may result in valve firing instability. To avoid this particular problem, a three-phase phase locked oscillator (PLO) is used instead which attempts to synchronize the oscillator through a phase locked loop with the commutating busbar voltages.

In the simplified diagram of the control system illustrated in Figure 3.8, the firing controller block (NPLO) consists of the following functional units:

- **i.** a zero crossing detector unit
- **ii.** ac system frequency measurement
- **iii.** a phase locked oscillator
- **iv.** firing pulse generator and synchronizing mechanism
- **v.** angle (α and γ) measurement unit, etc.

Zero crossover points are detected by the change of sign of the reference voltages and multiple crossings are avoided by allowing a space before marking the next crossing. Distortion in line voltages can cause difficulties in proper zero crossing detection, and the voltages must be smoothed before being passed to the zero crossing detector.

The time between two consecutive zero crossings, of the positive to negative (or negative to positive) going waveforms of the same phase, is defined here as the half period time, $\frac{T}{2}$. The

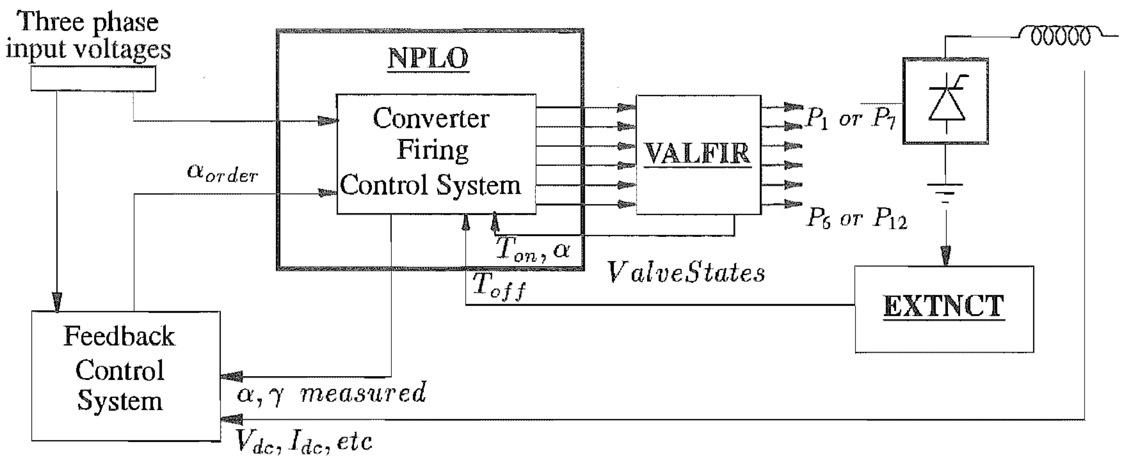


Figure 3.8 Phase Locked Oscillator based firing control mechanism

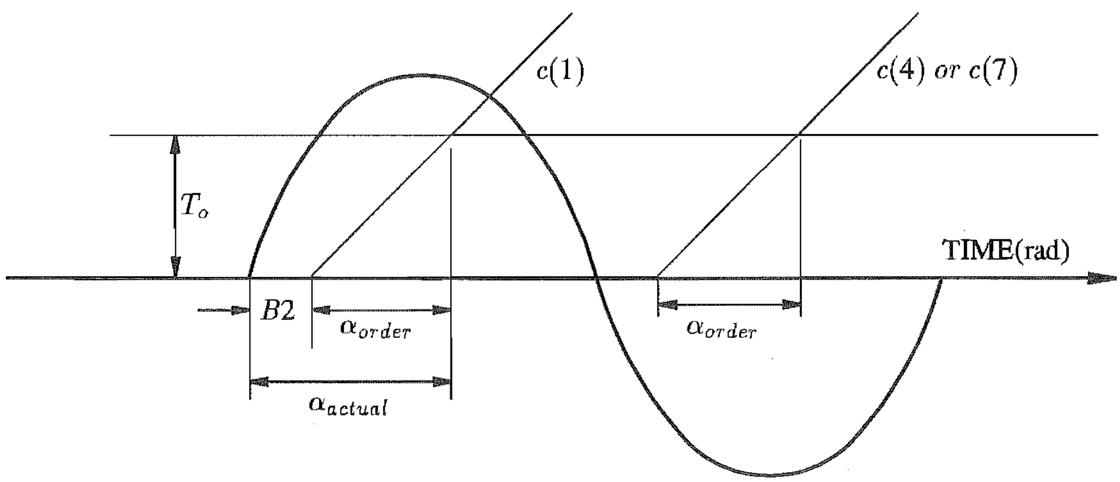


Figure 3.9 Synchronizing error in firing pulse (Source: Figure 7.3 of [EMTDC 1988])

measured periods are smoothed through a first-order real pole lag function with a user specified time constant. From these half period times the ac system frequency is estimated, every 60° (30°) for a 6 (12) pulse bridge.

Normally the ramp for firing of the particular valve ($c(1)...c(6)$) starts from the zero crossing points of the voltage waveform across the valve. After $\frac{T}{6}$ time ($\frac{T}{12}$ for 12-pulse), the next ramp starts for the firing of the next valve in sequence. So, α of 0° for the incoming valve corresponds to the end of $\frac{T}{6}$ time from the previous ramp and so on.

It is possible that during fault or due to the presence of harmonics in the voltage waveform the firing does not start from the zero crossover point, resulting in a synchronization error, B2, as shown in Figure 3.9. This error B2 is used to update the phase locked oscillator which in turn reduces the synchronizing error, approaching zero at steady state conditions. The synchronization error is recalculated every 60° (every 30° for 12-pulse).

The firing angle order (α_{order}) is converted to a level to detect the firing instant as a function of the measured ac frequency by

$$T_o = \frac{\alpha_{order}(rad)}{f_{ac}(p.u.)}. \tag{3.12}$$

As soon as the ramp $c(n)$ reaches the set level specified by T_0, as shown in Figure 3.9 valve n is fired, and the firing pulse is maintained for 120°. Upon having sufficient forward voltage with the firing pulse enabled, the valve is switched on and the firing angle recorded as the time interval from the last voltage zero crossing detected for this valve.

At the beginning of each time step the valves are checked for possible extinctions. Upon detecting a current reversal a valve is extinguished and its extinction angle counter is reset. Subsequently from the corresponding zero crossing instant its extinction angle is measured, eg. at valve 1 zero crossing, γ_2 is measured and so on. (Usually the lowest gamma measured for the converter is fed back to the extinction angle controller). If the voltage zero crossover points do not fall on the time step boundaries, a linear interpolation is used to derive them.

As explained in section 3.7 and further illustrated in Figure 3.8, the NPLO block coordinates the valve firing mechanism while VALFIR receives the firing pulses from NPLO and checks the conditions for firing the valves. When the conditions are met VALFIR switches on the next incoming valve and measures the firing angle otherwise, calculates the earliest time for next firing needed to adjust the step length. Valve currents are checked for extinction in EXTNCT and interpolation of all state variables is carried out. The valves turn on time (T_{on}) is used to calculate the firing angle and off time (T_{off}) is used for the extinction angle.

3.12 Testing the new firing controller operation

To verify the operation of the firing controller implemented in the TCS program, two cases are presented in Figures 3.10–3.12 using the same test system as in section 3.8. A constant α_{order} of 15° was used in the case of Figures 3.10 and 3.11, where a step change was applied at 0.5 s for five cycles by increasing the α_{order} to 75°.

Whereas in the case of Figures 3.11–3.12 an initial constant current control of 1.225 p.u. was set up and at 0.5 s the current order was reduced by 50 % for 5 cycles. The responses are compared with similar control implementations of EMTDC (with a 20μs time step) as shown in the respective figures. Complete agreement was found in all these cases which were considered sufficient for further comparisons of the TCS related results with those of EMTDC.

3.13 Conclusion

In this chapter the TCS program formulation and relevant aspects of its implementation have been discussed. Attention has been focused mainly on the operation of the HVdc converter and its simulation with explanation on the handling of switching discontinuities. A more flexible firing

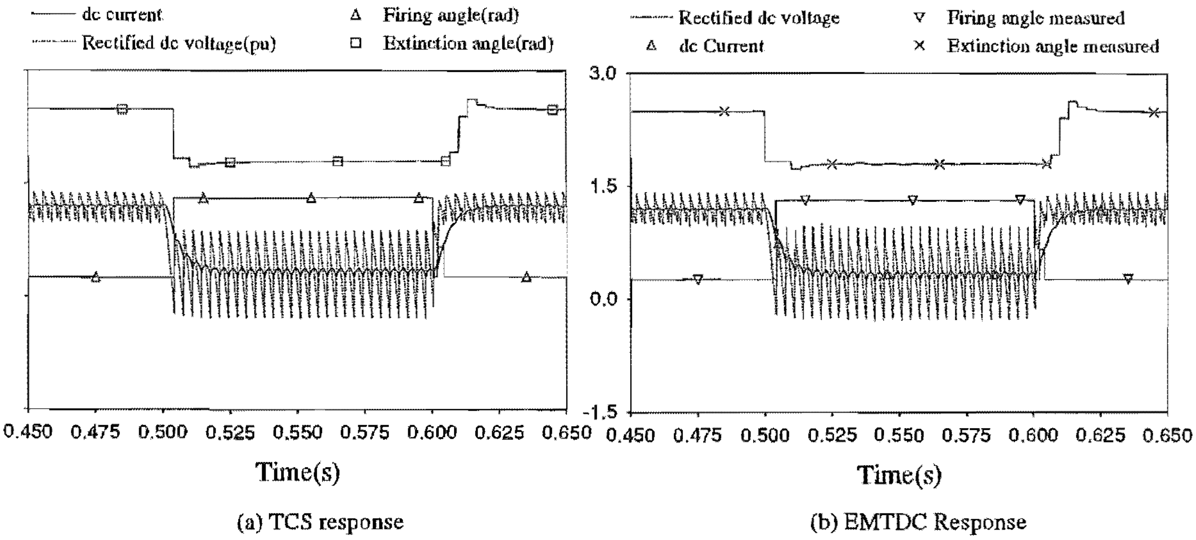


Figure 3.10 Constant α_{order} operation with a step change

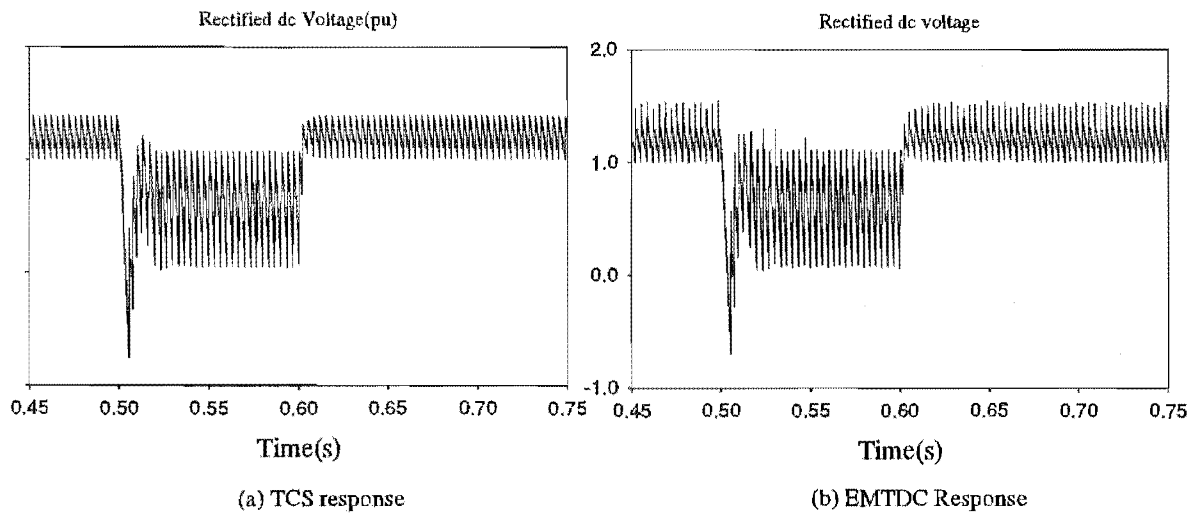
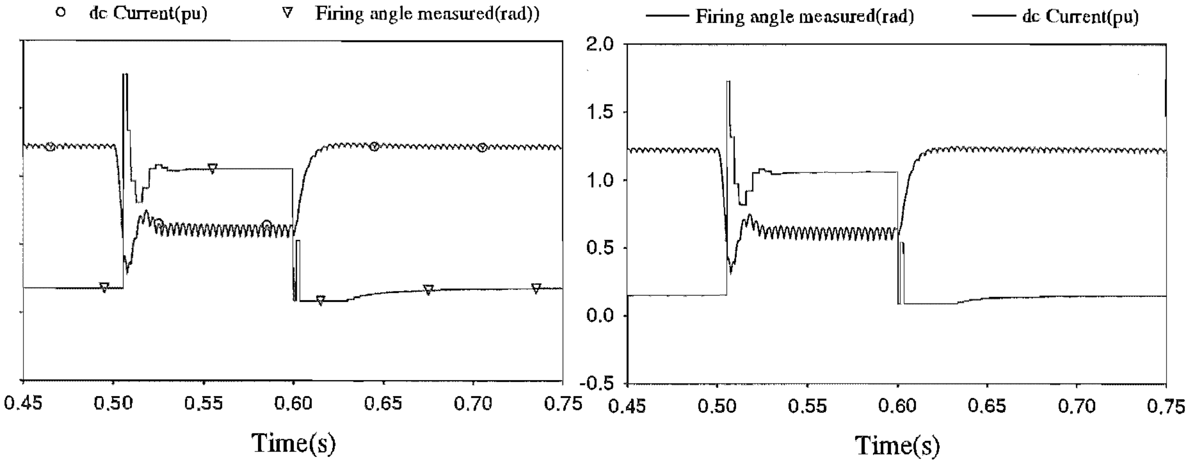


Figure 3.11 Constant current control with a step change; dc voltage

controller also based on the phase locked oscillator has been added to TCS and its performance verified.

It is clear, from the results, that the TCS state variable implementation, together with its ability to detect the discontinuities accurately and to dynamically select the time steps, provides very accurate solutions. The step length adjustment is also useful for handling other non-linearities, such as in the case of transformer saturation, where smaller steps will be necessary around the



(a) TCS response

(b) EMTDC Response

Figure 3.12 Constant current control with a step change; dc current and α

knee region, while larger strides can be taken elsewhere on the saturation characteristic (mostly linear or linearly extended part of the curve). This not only improves the accuracy of the solution, but also the stability of the overall solution by faithfully following the given characteristic of the non-linear devices.

With a converter connected to ideal ac and dc sources a very large time step of 1 ms was feasible, although the actual step was modulated under the program's control. This, resulting in extremely fast solution for the above system, suggests the possibility of being incorporated into a steady-state harmonic analysis program, where regular excursions are made to time domain, for devices with switching non-linearities such as an HVdc converter.

The valve extinctions are easily detected after the current reversal while valve firing and other forthcoming events can be predicted accurately. Both these detection and prediction help the program trace the state of the system closely. By tracking the convergence behaviour the dynamic step length modulation assists the overall performance of the program and permits larger time steps to be used; the maximum step is decided on consideration of the maximum frequency of interest.

Some of the main disadvantages of the state variable programs also apply to the TCS program. Although TCS can simulate any practical power system, with the size of the system representation the simulation time increases rapidly and a balance has to be met between accuracy and computational requirements. The allowable network topologies are limited by the constraints placed on the type of network components and their connectivity. The best features of the TCS program can be exploited by combining them with an efficient EMTDC program as discussed in chapter 4.

Appendix 3A TCS integration method

An implicit integration procedure, based on the trapezoidal approximation is used to solve the set of non-linear differential equations. This method has been developed for the solution of linear differential equations and therefore the step length must be consistent with the assumption of constant coefficients within the integration interval.
The system of state equations could be written as

$$\dot{x} = f(x,t) \tag{3.13}$$

where, x represents the state variables vector and t the time.
For each time step the change in a state variable Δx is equal to the integral of the area under its derivative, and the trapezoidal integration approximates this as

$$\Delta x = \frac{h}{2}(\dot{x}_t + \dot{x}_{t+h}) \tag{3.14}$$

where, $\dot{x}_{t+h}$ is determined iteratively as follows:

i. For an initial estimate assumed $\dot{x}_{t+h} = \dot{x}_t$.

ii. An estimate of x_{t+h} based on $\dot{x}_{t+h}$ estimate is obtained

$$x_{t+h} = x_t + \frac{h}{2}(\dot{x}_t + \dot{x}_{t+h}) \tag{3.15}$$

iii. $\dot{x}_{t+h}$ is estimated from the current x_{t+h} value using

$$\dot{x}_{t+h} = f(x_{t+h}, t+h) \tag{3.16}$$

iv. Steps (ii) and (iii) are performed iteratively until convergence is reached. Convergence is deemed to have occurred when all the state variables satisfy;

$$\varepsilon \geq \left| x_{t+h}^{j+1} - x_{t+h}^{j} \right|$$

where, ε is the state variable convergence tolerance. An additional convergence constraint is specified to ensure the state variable derivatives converge sufficiently;

$$\varepsilon_d \geq \left| \dot{x}_{t+h}^{j+1} - \dot{x}_{t+h}^{j} \right|$$

where, ε_d is the state variable derivative convergence tolerance.

Convergence is reached within 3 or 4 iterations normally. A maximum step length of approximately one degree of fundamental frequency will be sufficient to accurately sample the converter generated harmonics up to 2.5 kHz. With such small step-length the integration method has proven stable and sufficiently accurate, requiring only a few iterations to converge. To ensure fast convergence the integration step length is automatically adjusted at each integration step depending on the convergence performance.

Chapter 4

PROPOSED HYBRID SIMULATION METHOD

4.1 Introduction

The two alternative methods in current use for transient simulations have been discussed in chapter 2, and their advantages identified. An advanced algorithm based on the state variable method had been given special consideration in chapter 3. The Electromagnetic Transient (EMT) programs have been shown to provide very efficient representation of power systems and an elegant method of network connections, while the state variable programs provide the capability to accurately represent the switching devices and any other power electronic equipment. If an accurate modelling of switching devices and an economic but detailed representation of the rest of the system can be achieved an efficient transient simulation should result. The above factors indicate that, a combination of the best features of both state variable and EMTP methods, should yield a better overall performance.

4.2 Hybrid approach

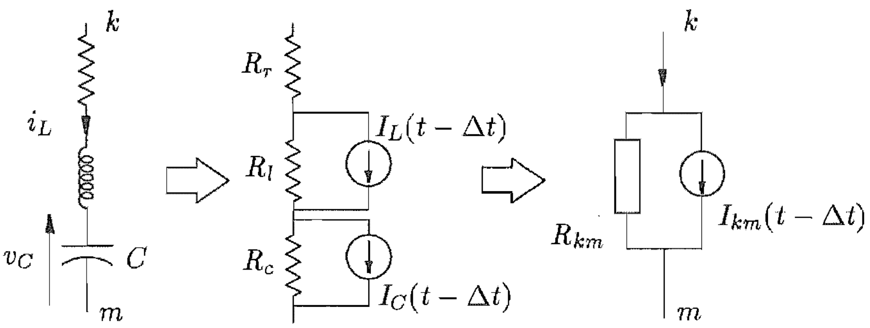
In this work a hybrid approach is proposed which not only keeps the models in their ideal environment but has them as groups within that environment and shares information by a stable interface at fixed intervals. Although the algorithm proposed in this work is applicable to any combinations of state variable and EMT programs, the hybrid technique is discussed here with reference to two programs specifically developed to solve HVdc transmission problems. These are TCS (Transient Converter Simulation) [Arrillaga *et al.*, 1983] and the EMTDC program of the Manitoba HVDC Research Center [EMTDC, 1988].

4.3 Choice of component modelling

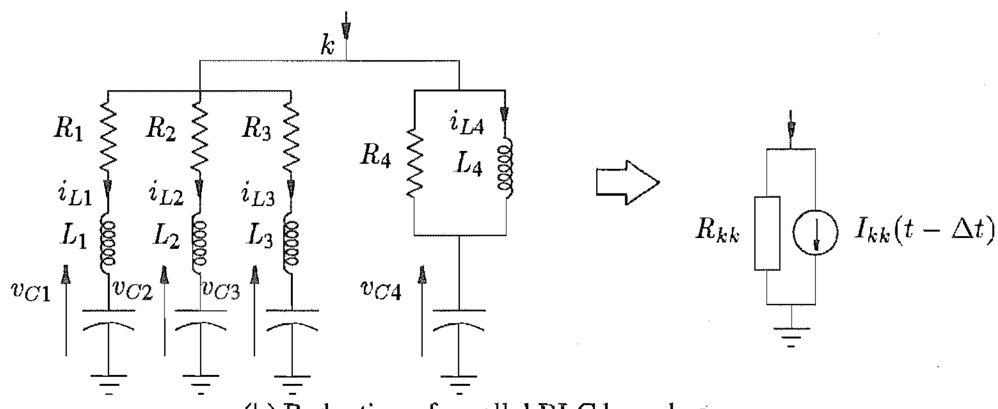
Until recently, the implementation of the EMT and state variable formulations have followed completely separate paths without regard to the best possible representation of each independent component. Breaking this barrier by combining state variable models and the EMTDC program Gole and Sood (1990) have demonstrated how a state variable model of a static var compensator represented as a stand alone subsystem can be interfaced to an electromagnetic transient program. State variable interfacing has also been proved successful with the synchronous machine model, which appears as a set of current injections to the EMTDC network [Woodford *et al.*, 1983; Gole *et al.*, 1984].

The state variable approach has shown to produce very accurate simulation of time varying topological networks, such as the HVdc converters and static var compensators. Each element of an R, L, C branch is modelled explicitly. Therefore, when the rest of the power system is also represented by the state variable program this results in heavy computational cost, owing to the increased number of state variables, the size of the system matrix and the increased switching frequency requiring smaller time steps solution for the entire network. The time step is modulated according to the frequency of switching.

The ac system simulation does not normally require very small time steps for accurate results and a 50 μs step has been found more than adequate. A common state variable representation of the ac system and the switching devices would require prohibitively high computer time and memory. In contrast, the EMTP method quickly reduces series or parallel RLC branches to a single equivalent resistor in parallel with a current source. As an example the four parallel RLC branches shown in Figure 4.1 have been reduced to a single branch. Of course, in the process



(a) Reduction of a series RLC branch



(b) Reduction of parallel RLC branches

Figure 4.1 Reduction of R,L,C branches to simple equivalent in EMTDC

the individual components have lost their identity and therefore, it is not possible to output the individual branch currents and voltages. However, if these are wanted the required branches can be retained. On the other hand, when using the state variable approach, eight state variables are required to represent the four branches, every inductor current and capacitor voltage contributing to one state variable each. The addition of further RLC branches would require extra state variables for their representation.

Normally in the state variable approach the transmission line is represented by π-sections, which increases considerably the size of the network matrix. Furthermore, the effect of frequency dependence cannot be modelled accurately in such an equivalent circuit.

Since the fixed step EMTP method is amenable to travelling wave models, an efficient representation of the transmission line is possible which is not available in the state variable solution. EMTP uses a modal analysis approach to model the transmission lines, which permits the inclusion of various effects collectively and thus reduces the computation time.

4.4 Component programs in hybrid environment

The structure of the component programs, EMTDC and TCS, have been discussed in sections 2.12 and 3.2 respectively. This section describes their presence in the hybrid environment facilitating a combined operation identifying the components for best possible representation.

4.4.1 EMTDC in hybrid environment

EMTDC constitutes the main program and handles the timing synchronization, requests data input (through an interactive dialog or in a batch mode) and also triggers a snapshot at the appropriate time. For realistic ac/dc system simulation the ac system must be represented in some detail around the converter busbars. The representation of the ac system and the associated slow varying components (those with large time constants) is best achieved as part of the EMTDC network.

When transmission lines are modelled by the travelling wave method the information available at one end of the line does not arrive at the other end until the delay time of the line. As this delay is of the order of milliseconds while the dynamic simulation time step is in microseconds this can be exploited to reduce the equations which represent the power system from one large matrix to a number of smaller ones separated by the transmission line [Wierckx, 1991] without sacrificing the accuracy of the solution. Efficient simulation results from the subdivision of the main matrix into diagonal blocks thus reducing the computational burden.

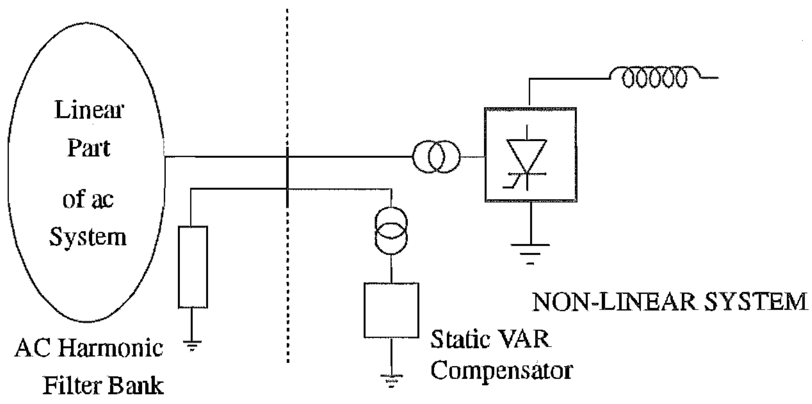
Apart from the presence of transmission lines, subsystem divisions can also be made if sufficient stable quantities exist at any point in the network. These subsystems are interlinked by a suitable interface at the point of subdivision. The interface remains unaffected for a duration of the main program time step requiring stable information (voltages and currents) referred across the interface. Conventional HVdc converters are ideally suited for interfacing as they possess a stable commutating bus voltage (a function of the ac filter capacitors) and a smooth current (a function of the smoothing reactor and the transformer leakage reactances).

4.4.2 TCS in hybrid environment

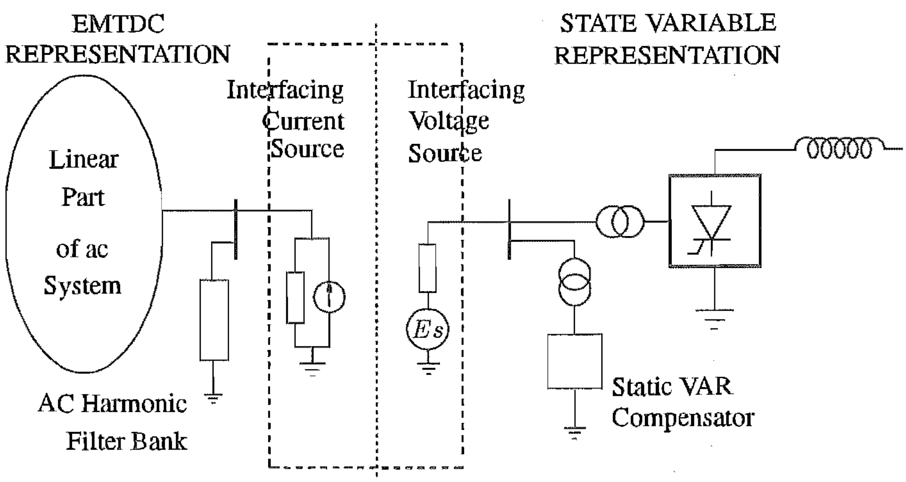
In the construction of the TCS system model the number of nodes increases proportionally the size of the system matrices and the computational burden. Consequently, the hybrid implementation should use TCS only for the switching devices and their surrounding components, although TCS is capable of modelling the complete HVdc/ac system. It is important to select carefully the components requiring state space modelling and this topic is discussed in section 4.5.

4.5 Implementation of the Hybrid algorithm

Having identified the benefits of separating the HVdc converters and other switching elements from the rest of the system, the two immediate questions to resolve are a suitable location for the system tearing and an appropriate interface between the torn subsystems.



(a) Network to be subdivided



(b) Divided subsystems

Figure 4.2 A three phase single port network interface between EMTDC and TCS

The system has to be subdivided to represent the components requiring the use of the state

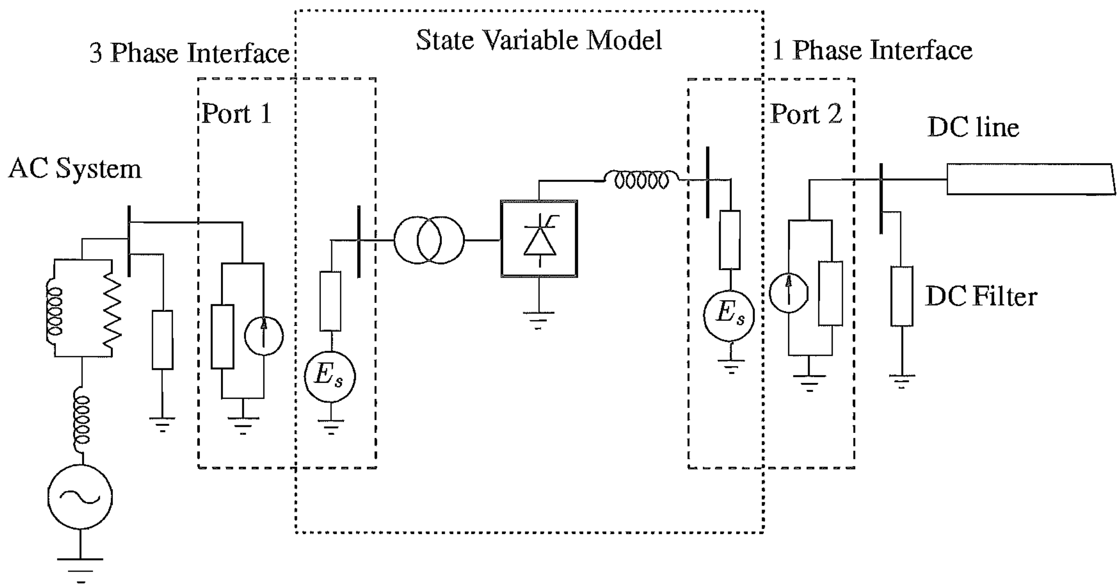


Figure 4.3 A two port interface between EMTDC and TCS

variable formulation. The key to a successful interface is the exclusive use of 'stable' information as mentioned in section 4.4.1. With reference to the d.c. converter system shown in Figure 4.2 (a), the tearing is done at the converter busbar as shown in Figure 4.2 (b). The interface between subdivided systems, as in the EMTDC solution, uses Thevenin and Norton equivalent sources.

If the d.c. link is represented as a continuous system, like the case of a back-to-back interconnection, only a three-phase two-port interface is required. A point to point interconnection can also be modelled as a continuous system if the line is represented by lumped parameters (at present only the pi section transmission line representation is supported in the TCS model). Alternatively, the d.c. line can be represented by a distributed parameter model, in which case an extra single-phase interface is required on the d.c. side as shown in Figure 4.3 to incorporate the EMTDC line model.

The main EMTDC program controls the timing synchronization, snapshot handling and operation of the state variable subprogram. The exchange of information between them takes place at the fixed time steps of the main program.

A Thevenin source equivalent is derived from the busbar voltages, and upon completion of a ΔT step by the state variable subprogram, the resulting phase current is used as a Norton current injection at the converter busbar. Figure 4.4 illustrates the four steps involved in the interfacing process.

Step (i) : The main program calls the state variable subprogram using the commutating busbar voltages (and the converter firing angle orders, if the control system is represented in EMTDC, as mentioned in section 4.6) as inputs.

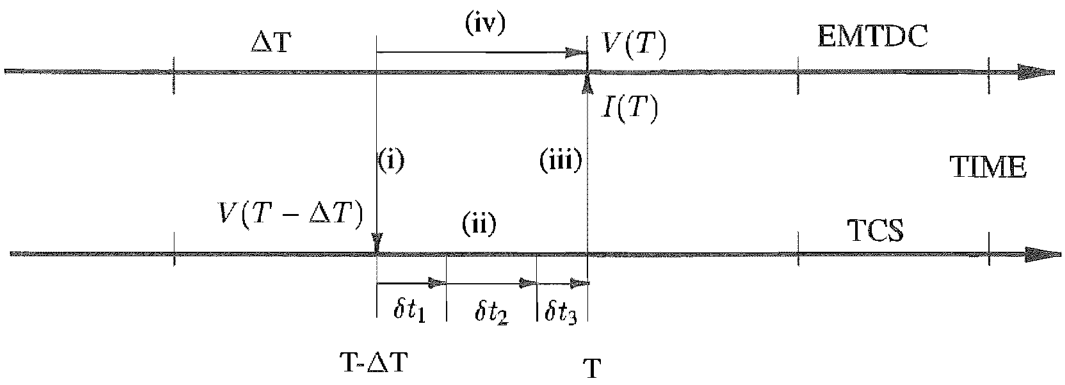


Figure 4.4 Timing synchronization

Step (ii) : The state variable subprogram is run with the new input voltages using variable time steps with an upper limit of ΔT. The intermediate states of the interfacing three phase source voltages are derived by the phase advancing technique (section 4.5.1).

Step (iii) : At the end of each complete ΔT run of step (ii) the interfacing Thevenin source currents are used to derive the Norton current sources to be injected into the a.c. system at the interface points.

Step (iv) : The rest of the system solution is obtained for a ΔT interval, using these current injections.

A ΔT value of 50 μs normally leads to stable solutions. The state variable multiple time steps vary from a fraction of a degree to the full ΔT time, depending on the state of the system. As the system approaches steady state the number of intermediate steps are reduced progressively.

4.5.1 Phase advancing technique

Three phase source voltages employed in the interfacing are phase advanced with time using the following equations:

$$\begin{aligned} V_a' &= V_a(t + \Delta t) \\ &= V_a\, cos(\Delta t) + \frac{(V_c - V_b)}{\sqrt{3}}\, sin(\Delta t) \end{aligned} \tag{4.1}$$

where, $V_a(t), V_b(t), V_c(t)$ are the phase voltages known at time t, and Δt is the required phase advancement.

This method is part of the EMTDC algorithm [EMTDC, 1988] when updated three phase quantities are needed within sub incremental time steps of a main time step loop. It has also been recently used by Gole and Sood (1990). The prediction using Equation (4.1) provides an approximation economically implemented and found to be adequate for practical purposes. The effect of the small error in waveforms introduced by the assumption of balanced sinusoidal waveforms under transient conditions is negligible for the short duration (typically < 1° at 50 Hz) over which the extrapolation is carried out.

4.5.2 Network tearing and interface

A simple example of subsystem division and network interface is shown in Figure 4.5. Although a single-phase network is used to illustrate the interface technique, this can easily be extended to a three-phase case.

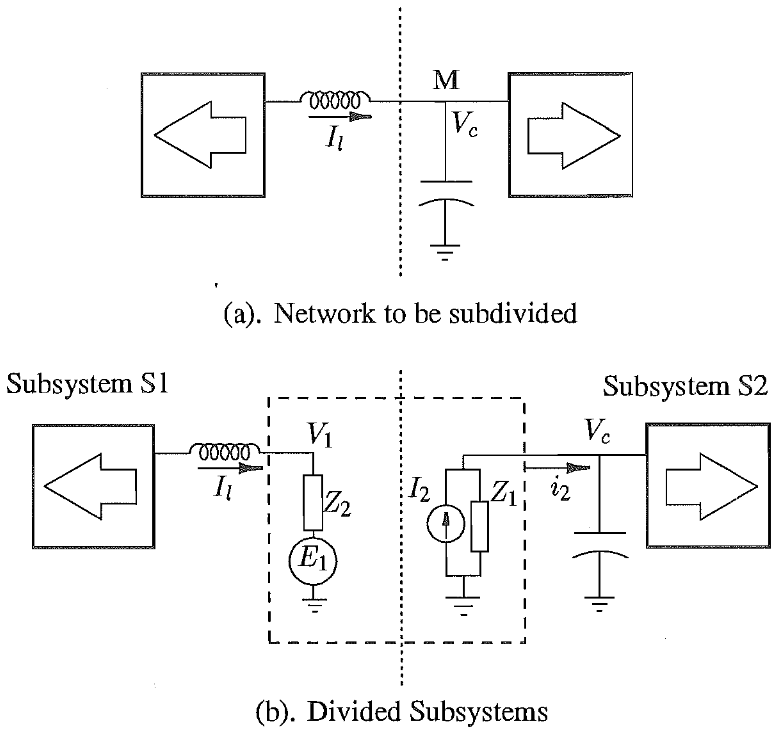


Figure 4.5 Network subdivision and interface

The system is broken into two subsystems at node M, a very stable point due to the presence of the inductor current for system S_1 and the capacitor voltage for system S_2.

An interface is achieved through the following relationships for the Thevenin and Norton source equivalents E_1 and I_2, respectively.

$$I_2(t) = I_L(t-\Delta t) + \frac{V_C(t-\Delta t)}{Z_1} \tag{4.2a}$$

$$E_1(t) = V_C(t-\Delta t) - I_L(t-\Delta t)\, Z_2 \tag{4.2b}$$

In Equation (4.2a), the value of Z_1 is the equivalent Norton resistance of the system looking from the interface point through the reactor and beyond. Similarly, In Equation (4.2b) the value of Z_2 is the equivalent Thevenin resistance from the interface point looking in the other direction.

The interface impedances can be derived by disabling all external voltage and current sources in the system and applying a pulse of current to each reduced system at the interface point. The calculated injection node voltage, in the same time step as the current injection occurs, divided by the magnitude of the input current will yield the equivalent impedance to be used for interfacing with the next subsystem.

4.5.3 Current compensation

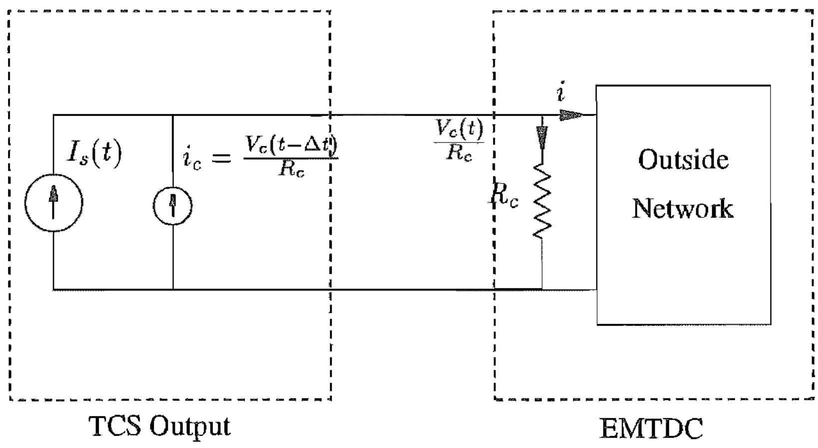


Figure 4.6 Current compensation in an interface (Source: Figure 8 of [Gole and Sood 1990] ©1990 IEEE)

As duly noted in references [Woodford *et al.*, 1983; Gole and Sood, 1990], numerical instability may arise when interfacing the state variable model to EMTDC. Because, the model interfaces to the parent program as a current source, whose value is not affected by the results of the calculations until one time step later, it appears like an incremental open circuit for a duration of the present time step in the parent program. To prevent this a fictitious resistance R_c can be added, the exact value of which is not critical. However, the short term behaviour of the interfaced model can be represented by R_c. Therefore the final current injection $I_s(t)$ has to be compensated to account for this extra branch current by adding the compensation current $i_c(t) = \frac{V(t-\Delta t)}{R_c}$ to the injected current.

Hence the actual current injection into the main network is

$$i(t) = I_s(t) + \frac{V(t-\Delta t) - V(t)}{R_c} \tag{4.3}$$

where, the second term in Equation (4.3) vanishes as $\Delta t \longrightarrow 0$, and so the current has a value nearly equal to $I_s(t)$, as was intended.

4.6 Control systems representation

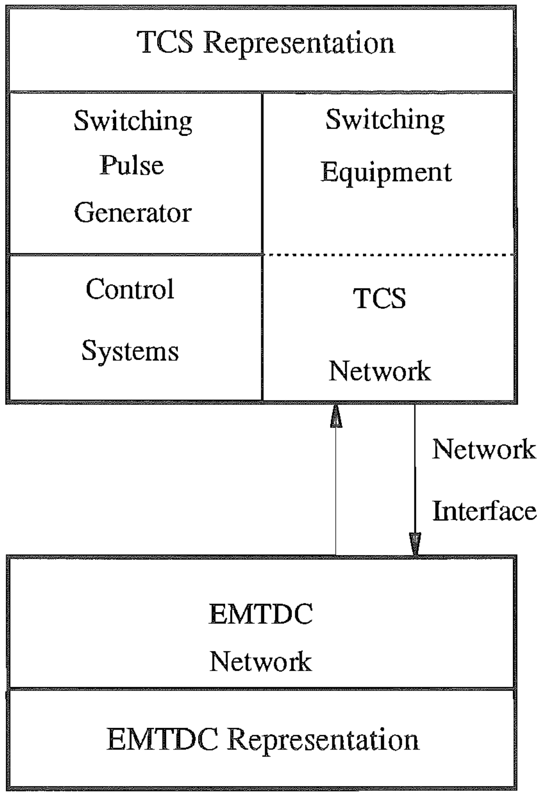


Figure 4.7 Control systems in state variable representation

This section discusses the simulation of the control system specifically related to the non-linear components of the state variable (TCS) subsystem down to the level where the control order signals are derived (i.e. the firing signals to the converter and/or other switching equipments).

Two options are available for the total control system representation, either with the controls modelled as part of the state variable program (Figure 4.7) or included within the main (EMTDC) program (Figure 4.8). The firing angle order is generated by the feedback control system (external to the converter model) based on the system conditions, ordered current, power or extinction angle requirements, and special protection measures which get translated into firing pulses by the switching pulse generator. In both options the switching pulse generator produces the signals required to trigger the switching (valve) elements and the EMTDC Network block represents the linear power network including the distributed transmission line models. When the control system is part of the TCS solution, it is built up from a library of building blocks as specified in a data file. The control system blocks are then solved iteratively at every step of the state variable solution until convergence is reached with an acceptable tolerance. All the feedback variables are immediately available for further processing of the control system within the TCS program.

Alternatively, when the control system is represented within the EMTDC program, the CSMF (section 2.12.3) function library becomes available and allows any generic or non-conventional control system to be built with the help of FORTRAN program statements. In

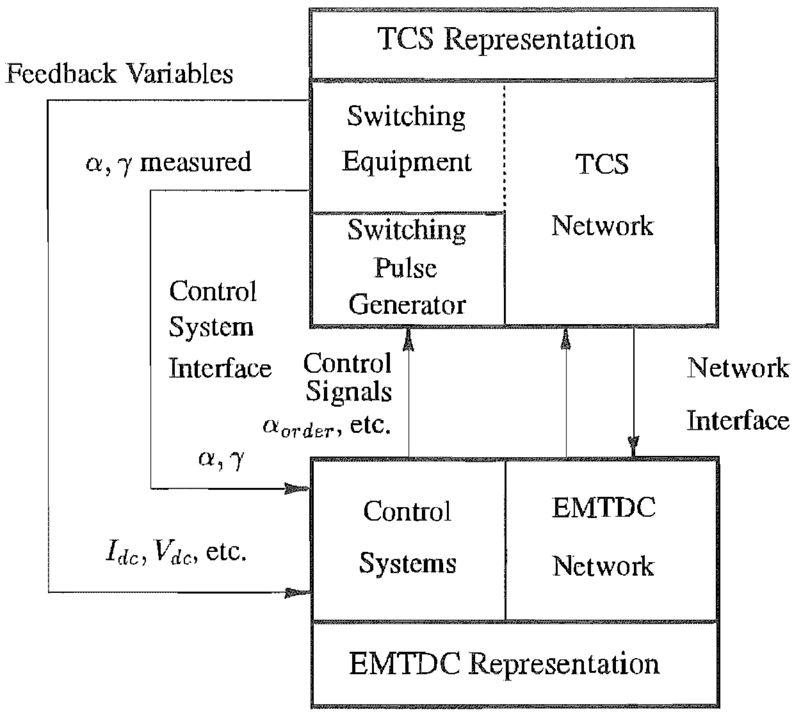


Figure 4.8 Control systems representation in EMTDC

this case, the main program must be provided with all the feedback variables required to define the states of the switching equipment (e.g. the converter firing and extinction angles, the d.c. voltage and current, commutation failure indicators, etc.). The control system is solved at every step of the main program sequentially; this is perfectly acceptable, as the inherent inaccuracy of the sequential function approach is rendered insignificant by the small calculation step needed to simulate the electric network and the usual delays and lags in power system controls [Woodford *et al.*, 1985].

4.7 Computer Implementation of the hybrid method

This section briefly outlines the necessary steps for the computer implementation of the hybrid method and its input/output requirements.

Appropriate network components are selected according to the criteria mentioned in section 4.5 for TCS and EMTDC representations. Additionally, the interfacing Thevenin and Norton sources are represented in TCS and EMTDC respectively. The TCS representation utilizes internal information on node/branch references, identifying the elements involved, to complete the interface.

Starting from the input data the main EMTDC program controls and synchronizes the operation of the child TCS program through its user defined subroutine DSDYN as shown in Figure 4.9. In DSDYN the excitations and the feedback control system according to option of Figure 4.8 are defined. For the control option of Figure 4.7 a separate controller data file is

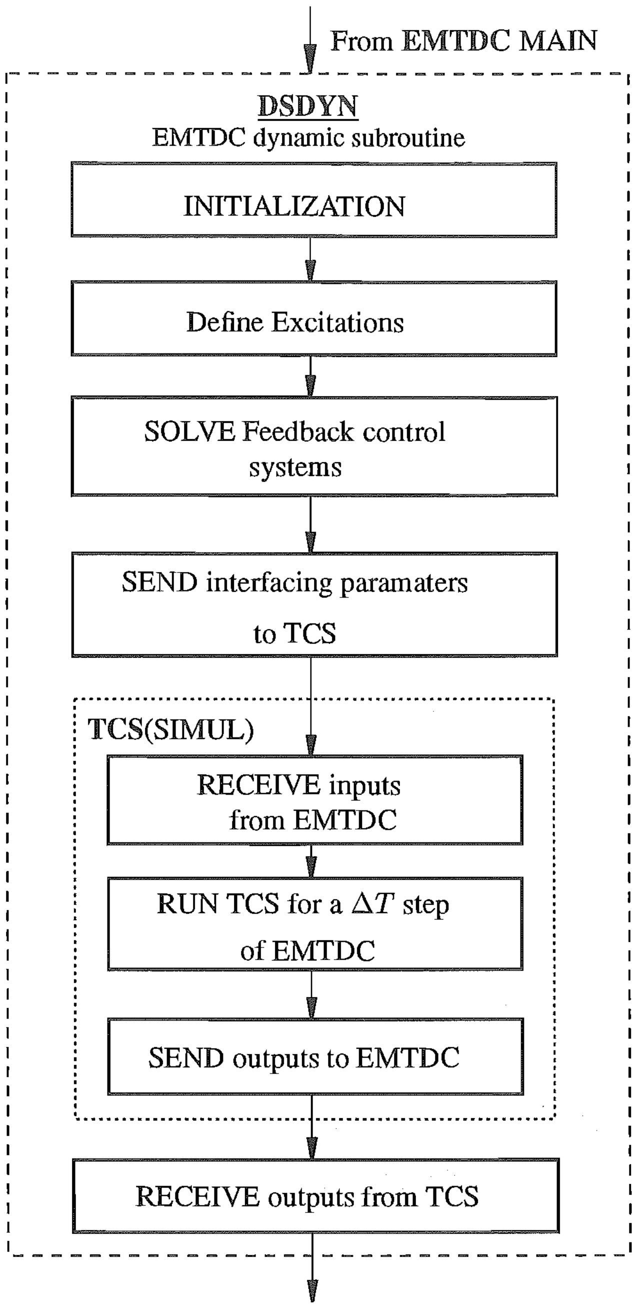


Figure 4.9 Subroutine DSDYN for Hybrid simulation

assembled.

At every step of the main program the relevant interfacing quantities (see section 4.5) are passed as inputs to the TCS program, which is then executed with variable step length operation for a total duration of ΔT time, the main program fixed time step. The total TCS operation is controlled by SIMUL, which carries out the input/output with the EMTDC and activates the main time step loop via MASTER as shown in Figure 4.10. The converter operation is monitored and controlled by MONITR, which is detailed in Figure 4.11. Any valve switching will be used to

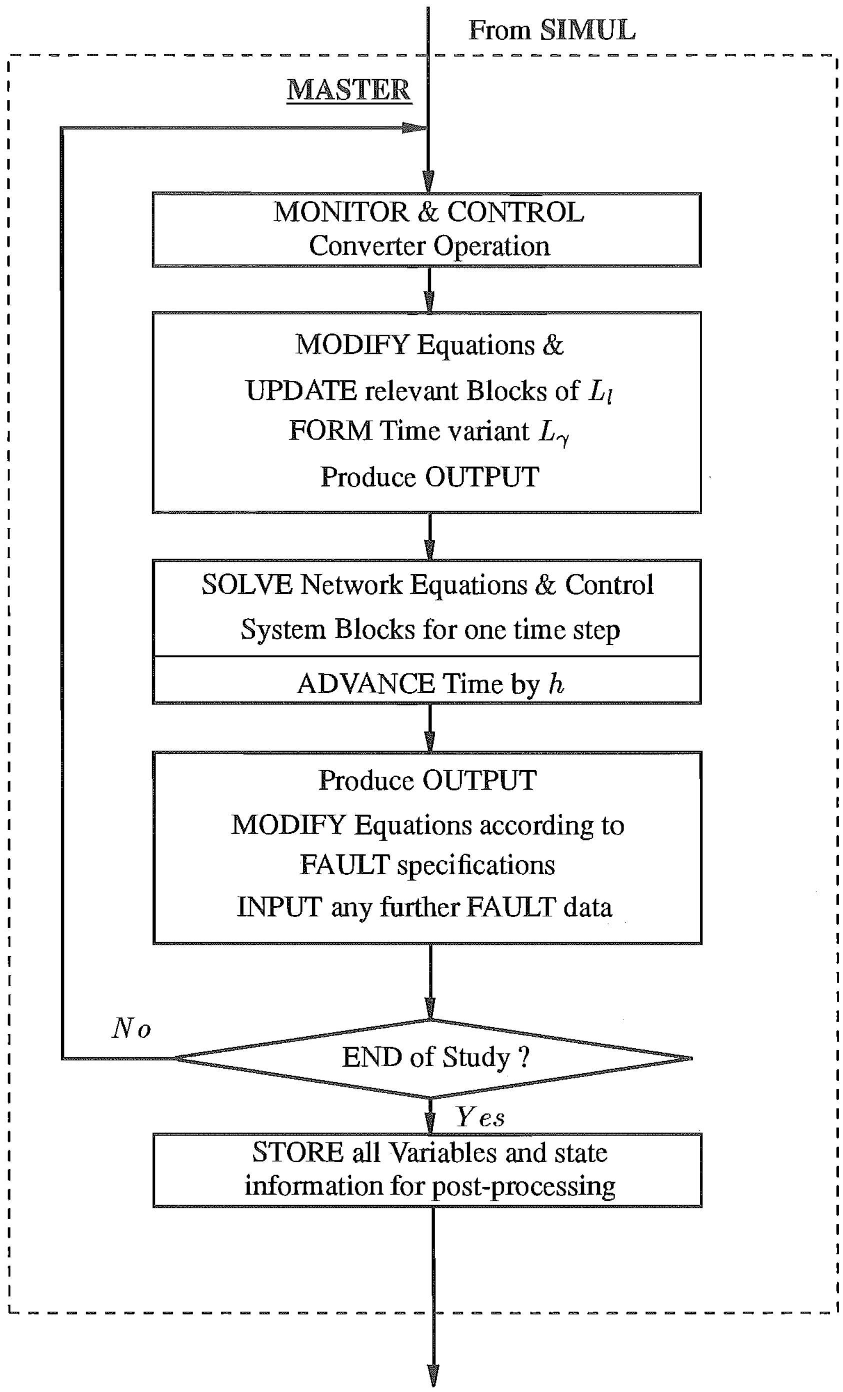


Figure 4.10 MAIN TCS simulation loop

implement a change in topology and a corresponding modification to the state equations. Once the TCS solution is obtained the TCS time is advanced by a suitable step length h, determined by the automatic step length adjustment with a maximum limit of ΔT, accompanied by a phase advancement of the interfacing sources. At the end of this ΔT interval the interfacing quantities are transferred to the EMTDC program, where a final solution is obtained to complete one step of

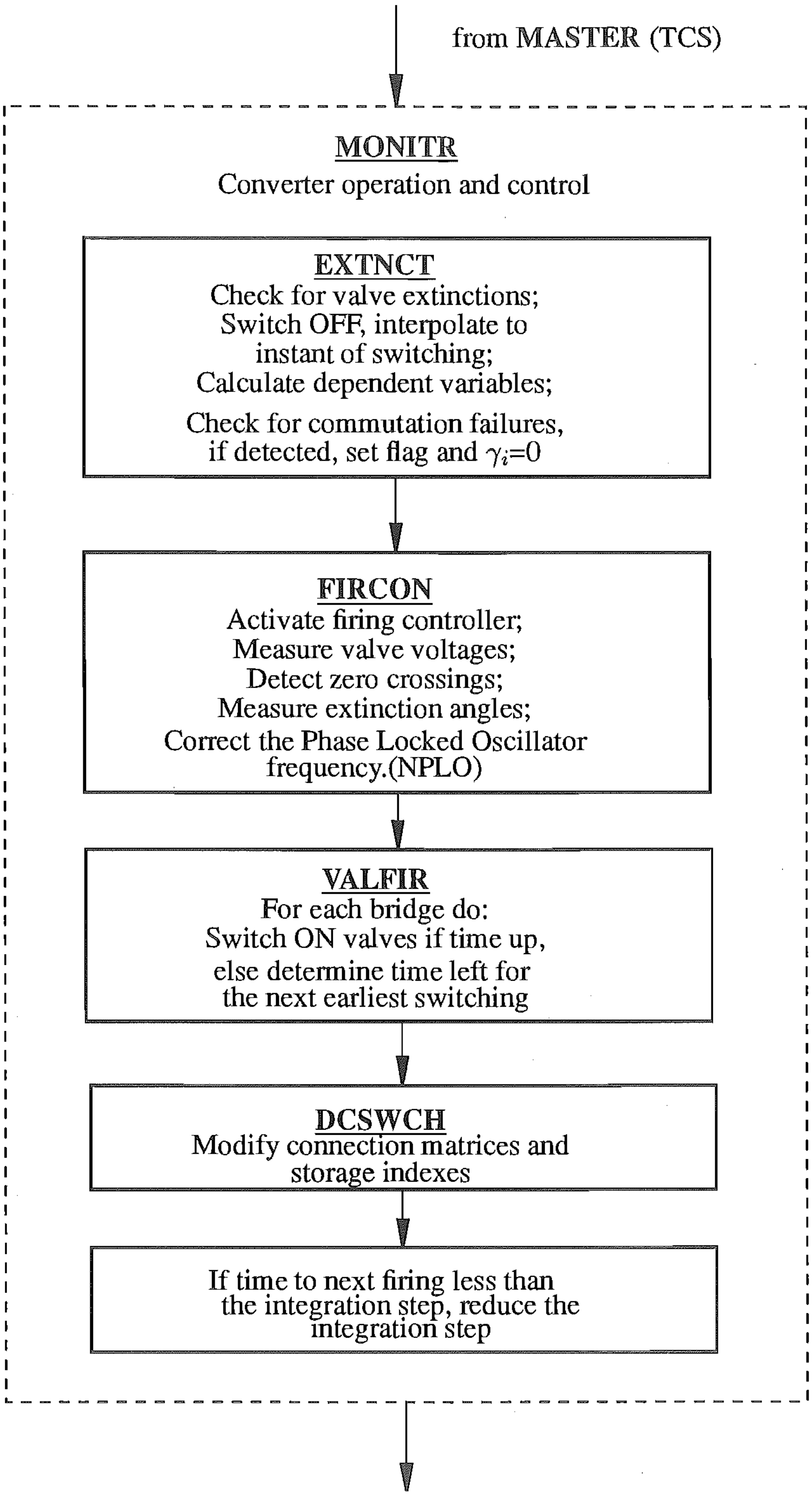


Figure 4.11 Monitoring converter operation and control

hybrid solution.

A snap shot can be taken at any time which will form the starting conditions for a new run. The snapshot handling is carried out under the main EMTDC program's control. The user's responsibility, apart from defining the simulation dynamics and building the control systems, includes separating the network into EMTDC and TCS parts and completing the interface. A user friendly algorithm requires a simpler assembly of the network and automation of the interfacing process.

4.8 Conclusion

A hybrid implementation, which has the capability of marrying the two different simulation techniques, an EMT program (EMTDC) and a state variable program (TCS), has been realized. The best possible representation of the components for accurate and efficient transient simulation has been identified. Although both programs are capable of modelling the complete HVdc/ac system only the switching devices and their surrounding components are represented in TCS, while the rest of the system is represented efficiently using EMTDC. Their combined operation is realized by a stable interface between the two programs sharing information across the interface boundaries and by maintaining the two programs in synchronized operation. As the information is exchanged at fixed EMTDC step intervals larger than the variable step length operation of the TCS, the intermediate TCS information is derived using a phase advancing method. However, the present phase advance technique used in the three-phase interface is not ideally suited to the simulation of asymmetrical conditions and a more effective extrapolation method must be developed to improve the prediction.

No attempt has been made to improve or modify the basic operation of the EMTDC algorithm. With a sufficiently stable interface such modifications to the EMTDC solution is not necessary. To avoid the inherent one time step delay, the EMTDC and TCS solutions can be iterated within the same EMTDC time step loop. However, continued use of such an iterative solution is computationally expensive and will render the method inefficient.

In the EMTDC program, the solution time is generally a function of the fixed time step, whereas in the TCS it varies depending on the state of the system as well, requiring shorter time steps during transient conditions. The automatic time step adjustment in TCS improves the overall efficiency while maintaining the required accuracy.

Chapter 5

SIMULATION RESULTS

5.1 Introduction

This chapter describes the simulation capability of the hybrid approach, presents the simulation results and validates the performance of the hybrid method.

The object of transient simulations is to reproduce the responses had the real system experienced similar conditions, without the need to subject the actual system components to possible extensive damage or disrupting the service of the system under operation. Digital simulators, when required to take over the function of the transient network analyzers (TNA), will need to prove their validity and ability to represent such systems effectively and efficiently. The validity of any simulation tool has to be verified with the known system responses, before being assigned the function of predicting results for an arbitrary system with confidence. In the absence of actual system responses an alternative could be the TNA model responses. When neither real system responses nor TNA results are available, an alternative means of model verification is the use of an already validated simulation tool. The main problem with verifying simulation tools is often not the restrictions on modelling different components but unavailability of the complete detailed system data and the control system descriptions. For example, it had been found that a difference of one millisecond in delayed response in the output of a dc current transducer had a significant impact on the response of the simulation model to converter transformer core saturation instability [Woodford *et al.*, 1985]. Furthermore, it can be shown that any differences in the firing control system alter significantly the transient behaviour of the ac/dc system. A comparison of two different simulation tools, thus requires the same conditions to be represented, in both, to a physically acceptable limit.

In order to validate the performance of the hybrid approach, therefore, simulation results were compared with EMTDC, an already validated digital simulation tool. The EMTDC program has been validated against real system responses from field tests and against the widely accepted EMTP program for transient simulations [Woodford *et al.*, 1985; Woodford, 1985; Ino *et al.*, 1985]. Moreover EMTDC is specifically written for the simulation of ac/dc systems based on the EMTP method. Using the EMTDC as the main program in the hybrid approach ensures similarity of system representation in both programs. The control systems were represented sequentially using basic building blocks from the EMTDC CSMF functions library. In the hybrid approach the control system representation is according to the interface option shown in Figure 4.8.

For all practical purposes the same parameters were used for the test system in both programs; there are, however, small differences due to their modelling requirements, eg. snubber circuits are connected in parallel with the valves and the valves represented by a binary resistance in the EMTDC program, whereas the hybrid approach represents the valves as ideal switches.

5.2 Initial conditions

Normally the starting point of the dynamic simulations is a complete steady state solution before any further disturbances are applied. The use of a steady state analysis such as load flow could provide the state of the system voltages and currents based on a single phase balanced situation. If an ac/dc load flow program is available it is possible to include the dc system equivalent together with the connected balanced ac system. A 3 phase ac/dc load flow program will provide a more detailed solution capable of representing an unbalanced ac system.

However, the load flow initializations can only provide a closer approximation to the actual initial conditions. A steady state analysis such as a load flow is based on the assumption of balanced (single phase) or unbalanced (three phase) sinusoidal ac waveforms. This may or may not result in approximate observance of the steady state conditions during the dynamic simulations, because the result is a function of non-linearities, and of unpredictable transients; for instance in the case of HVdc converters it is not possible to represent exactly the commutation sequences and filter currents. As a result the initial values of the system variables may be in error. A better initialization method is thus necessary for the dynamic simulation which should include the initial valve state specifications and synchronization of the firing pulses to the reference sources.

5.2.1 Dynamic initial conditions

Although some form of initialization can be built into the transient simulation algorithms to speed up the start up instead of starting the system to settle down naturally, it may still need a few cycles run to reach the actual steady state conditions. Sometimes it is necessary to artificially alter the time constants of the system to arrive at the steady state before bringing in the actual parameters for transient simulations [Heffernan, 1980].

When such initialization procedure is not used such as in the case of EMTDC, it is necessary to run the model to steady state conditions and freeze all the variables in the snapshot file which is really a kind of data file with everything properly initialized. It may be considered disadvantageous to start the system from an unspecifiable state to steady state, particularly when the model contains inherent instabilities which may be instigated under transient conditions although not clearly evident in its normal operating states; under such conditions it may never reach a steady state or may require excessive computer time to do so. Generally, trying to start the model by bringing it to steady state is a valuable exercise in itself. It can tell how robust the model is and if it fails to reach steady state, provides an indication that problems exist which will require attention [EMTDC, 1988].

The TCS algorithm provides some means of initializing the system with the given steady state conditions, however, the system may need a few more cycles run before achieving the actual steady state. The main problem is in the accurate specification of the voltages, currents, and valve conduction patterns during the commutation periods. A combination of the two programs EMTDC and TCS, thus, requires the system to start up in a coordinated manner. Following the start up methods normally used by EMTDC was found adequate to bring the hybrid simulation to steady state. The use of EMTDC as the main program enables the ac system sources to be ramped up from an unenergized state to bring the dc voltage to the normal value. This is normally done in EMTDC in order to make sure that the system starts up without resorting to oscillations. These oscillations are partly related to the natural behaviour of the system, and partly due to the combined behaviour of the initialization process of the different numerical models in the system. When starting from load flow conditions, improper initialization of a control model may cause null control signals during a few steps at the beginning of a run resulting in unexpected transients. Also, it has been found that, if an electrical resonance exists on the dc side at or near fundamental frequency and if the converter feeds from an ac system with a high second harmonic impedance, core saturation instability can result [Woodford, 1985].

The use of flexible control system modelling by EMTDC allows the action of the control circuitry to be represented in detail. Generally the startup process of an HVdc link follows a systematic process in order to avoid any possible excitation of the system oscillations. The *start-control unit* [Kimbark, 1971] of the control system is designed to increase the direct voltage exponentially without overshoot instead of in a step. This unit is functional only during the start up or the unblocking of a bridge.

The start-control unit provided with each converter performs two functions:

i. On the unblocking of a rectifier bridge, its start-control unit lets the direct voltage of the bridge rise exponentially to its normal value, with a long time constant compared with the natural frequency of the dc line, thus preventing any considerable overshoot of voltage.

ii. On the unblocking of an inverter bridge, its starting unit first causes the bridge to operate momentarily as a rectifier in order to extinguish the bypass valve and thereafter lets the direct voltage rise exponentially to its normal value.

Detailed control system modelling reflecting the actual control systems is a reality with the EMTDC program [Woodford, 1985]. Therefore, in the hybrid method, as in EMTDC, any type of control system could be modelled, and non-linear gains can be introduced for the various control system blocks as and when necessary. Often the limitation is the unavailability of complete control system data. It is difficult, on the other hand, with the TCS type of modular data file to simulate these type of time varying control, if not impossible. However, TCS provides most of the basic minimum control system blocks required for building a continuous control system through the data file.

5.3 Test systems representation

For the assessment of the hybrid approach performance and capabilities, in different aspects, four test systems were selected. The first test system (Test system 1), a back-to-back dc link, was used to highlight the steady-state performances and to show the quality of the resulting waveforms. Transient performances are discussed with reference to the Test systems 2, 3 and 4.

Test system 2 models a point to point dc link with the dc line represented by the EMTDC distributed parameter line model. This also shows the possibility of a two port interface to a state variable converter model. In order to show the modelling capability of the control systems by the hybrid approach a detailed power controller is introduced into the Test system 3 which is identical to the Test system 2 except for the representation of the dc line using five-pi sections instead of the distributed parameter model. This shows the possibility of the dc system to be completely represented as a continuous state space based subsystem.

The ac/dc system interactions are assessed properly when the system around the converter is represented in detail. This is achieved in Test system 4 by extending the rectifier side ac network equivalent to a four bus ac system spanning away from the converter terminals.

5.4 Steady-State Performances

Test system 1, shown in Figure 5.1, is used to compare the steady state performances of the EMTDC and hybrid approaches. The ac systems are represented by simple Thevenin equivalents with the same damping at fundamental and third harmonic frequencies. Ac harmonic filters are provided with 11^{th}, 13^{th} tuned filters and a high pass filter with a lower cut-off frequency at 24^{th} harmonic. A simple controller, with the rectifier on constant current control(CCC) and the inverter in minimum extinction angle control(EAC) is used. The relevant system data is presented in Appendix 5A. These simulations were carried out on a SUN-SPARC 2 workstation.

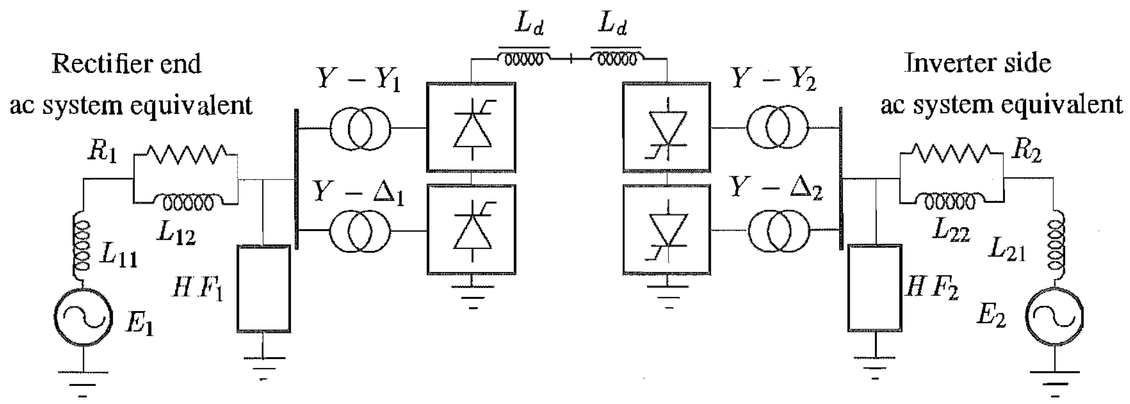


Figure 5.1 Test system 1; back-to-back dc link

5.4.1 Hybrid Simulation

The test system was subdivided to satisfy the modelling requirements for the hybrid method and the interfacing was carried out as explained in chapter 4. This resulted in two subsystems representing the two ac side networks and a continuous state variable subnetwork in TCS representing the dc system as shown in Figure 5.2. A 50 μs (1.08 degrees at 60 Hz) step width was used for the main program and the ac systems, and as the maximum step width for the state variable model.

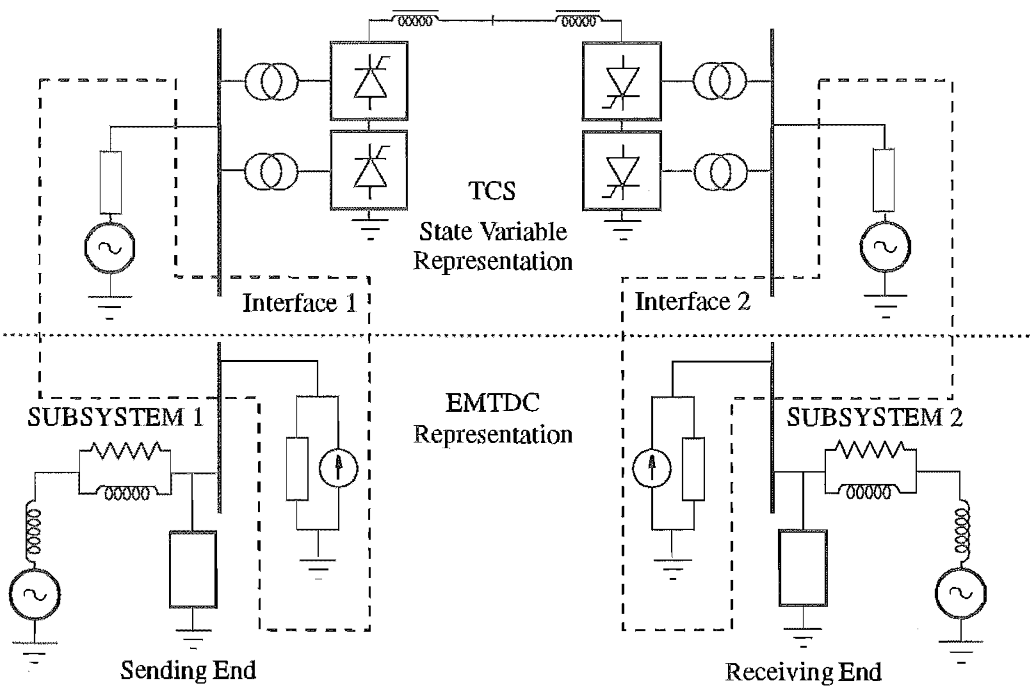


Figure 5.2 Hybrid representation: back-to-back dc link

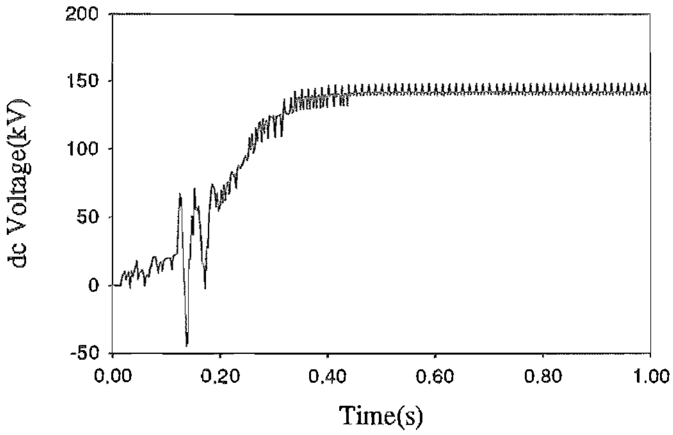
The system was started from a deenergized state by ramping up the ac voltage sources and the current order in 0.28 s. Both converters were blocked initially and they were subsequently deblocked, the inverter after 0.05 s and the rectifier at 0.12 s. Although the steady state was reached around 0.5 s, simulation was carried out up to 1.0 s.

The start up response of the dc mid point voltage and dc current are shown in Figure 5.3. Steady state waveforms are presented by expanding the responses for one cycle of fundamental frequency. Expanded dc voltages at rectifier end, inverter end and at the mid-point are shown in Figure 5.4. Waveforms of the dc current and the rectifier total ac input current are shown in Figure 5.5. At sudden voltage transitions, the sharp dents observed in the rectifier dc voltage are due to the effect of inverter switchings and vice versa, which can be expected as the rectifier and inverter deform their respective valve voltages in a back-to-back operation. These waveforms obtained with the hybrid method are repeatable and represent the ideal physical behaviour. A CPU time of 327 s was required for a simulated real time of 1.0 s.

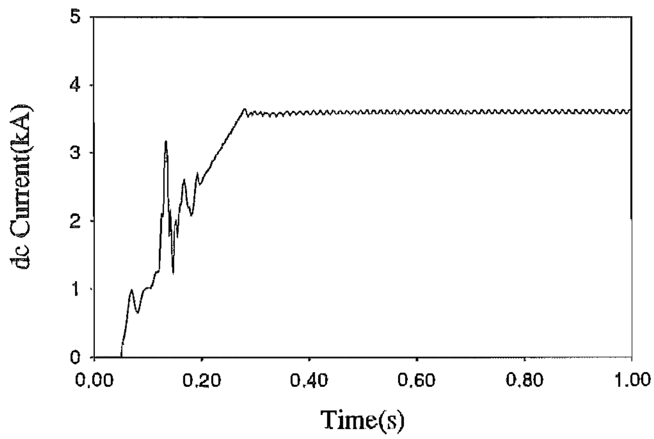
5.4.2 EMTDC Simulation

In the first place, the EMTDC system was also run with a 50 μs time step throughout. The system was separated into three subsystems with the conventional modular converter model representation, where the converter module was solved with five submultiple time steps (ie. an effective time step of 10 μs for the converter solution). Subsystems 1,2 and 3 represent the rectifier ac side, inverter ac side and the dc side subnetworks respectively.

Similar starting conditions were given to the system as mentioned for the hybrid simulations and the steady-state was reached before 1.0 s. For comparison with the hybrid approach the dc



(a) dc voltage at mid-point



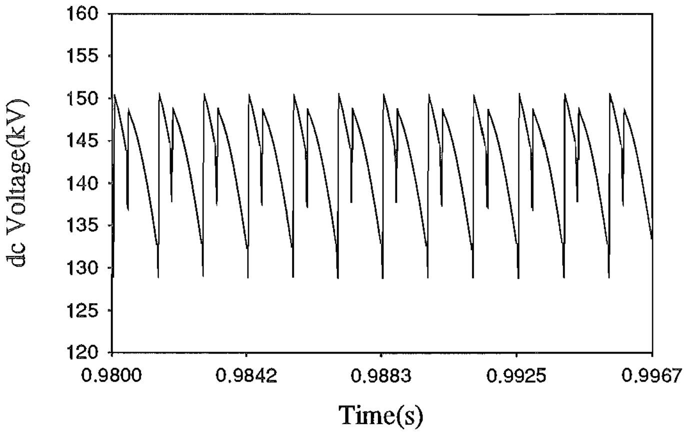
(b) dc current

Figure 5.3 Test system 1 start up response: Hybrid method

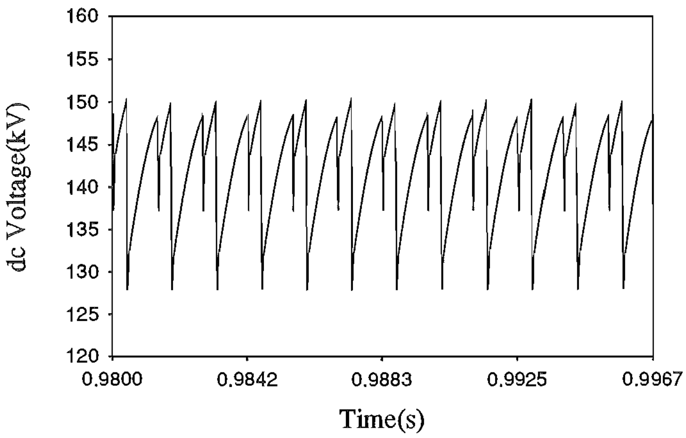
voltages at rectifier end, inverter end and the mid point are shown in Figure 5.6.

These responses show spurious spikes in the steady state waveforms during the switching transitions which could be reduced, eg. by tuning the snubber circuit parameters to introduce extra damping. However, the additional damping may affect the transient response accuracy significantly [Maguire and Gole, 1991]. One way to avoid these oscillations is to solve the system with a sufficiently small step width and a 10 μs step is found adequate, although not being able to pin point the switching instants which may not fall on the time step boundaries. The resulting responses are shown in Figure 5.7. The CPU times required for the 50 and 10 μs cases are 150 and 697 seconds respectively.

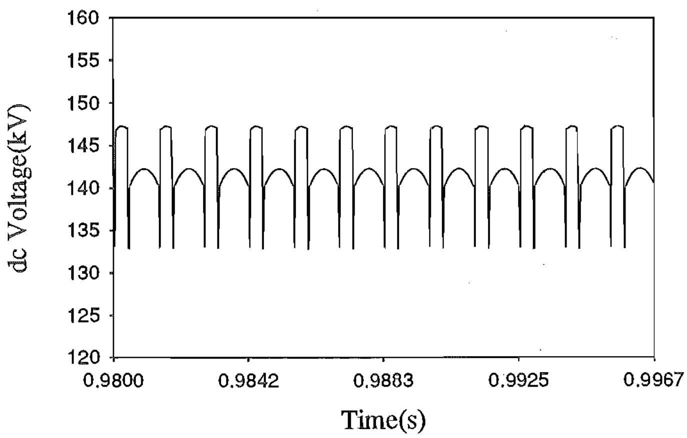
This step width reduction is only one of the possibilities to get a better response. However, in this case, a very small time step was needed to avoid the spikes in the waveforms and to reproduce the exact waveforms.



(a) Rectifier end

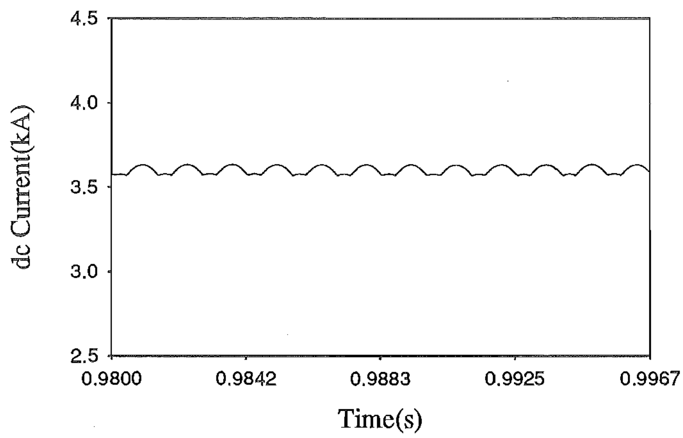


(b) Inverter end

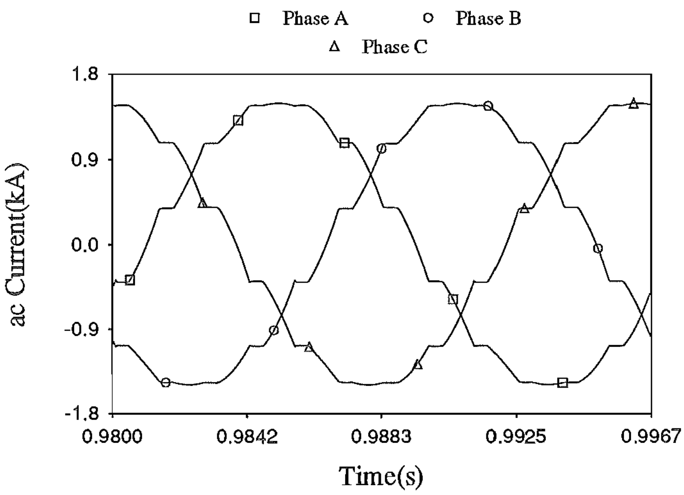


(c) Mid-point

Figure 5.4 Steady state dc voltage waveforms: Hybrid method



(a) dc current

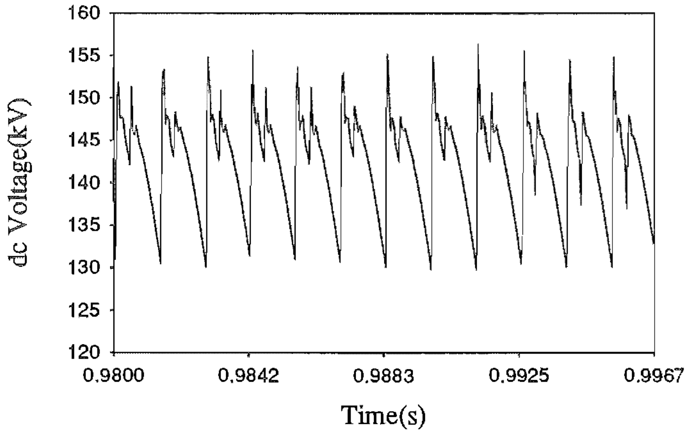


(b) total rectifier input ac current

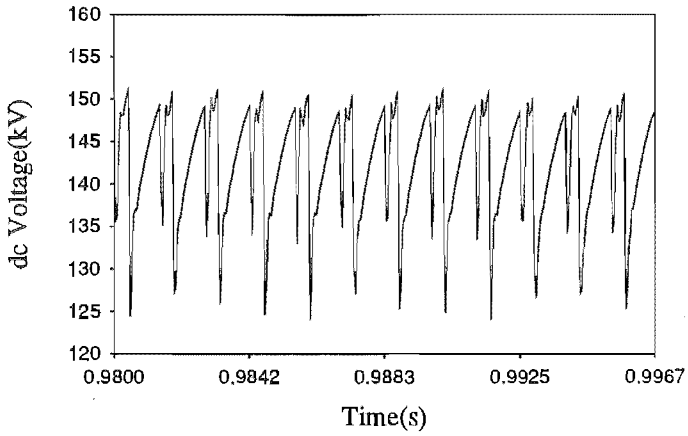
Figure 5.5 Steady state current waveforms: Hybrid method

The following points can be deduced from the above results:

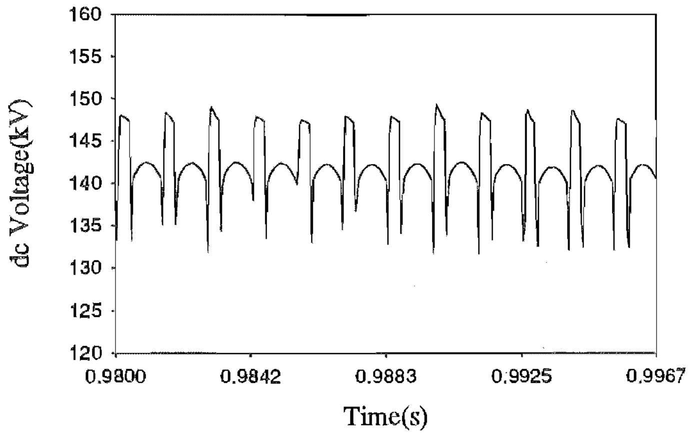
- The oscillations observed with the EMTDC solutions are not related to the physical reality, rather it is a problem of the numerical process. When reducing the step width the oscillations disappear, signalling that the longer the time step interval more severe the spurious spikes are.
- By exactly locating the switching instants the hybrid approach could produce better responses without the need to reduce the main program time step or tuning additional parameters to improve the numerical stability.



(a) Rectifier end

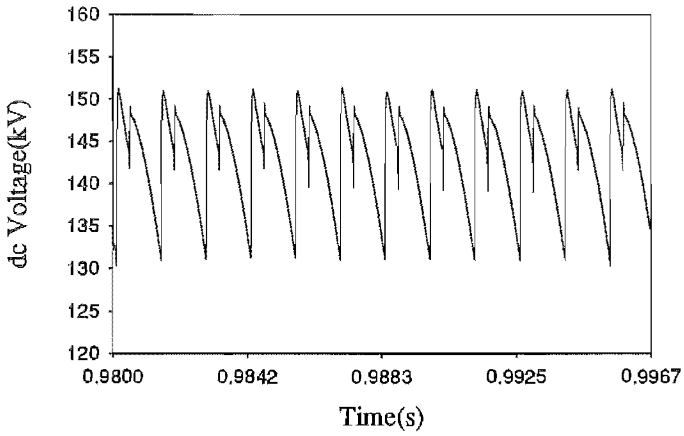


(c) Inverter end

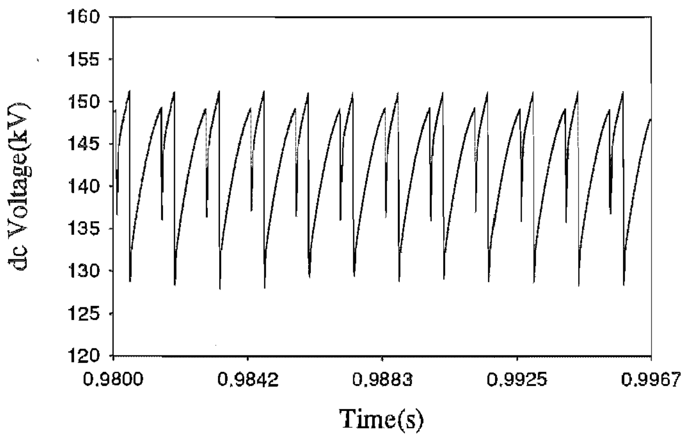


(c) Mid-point

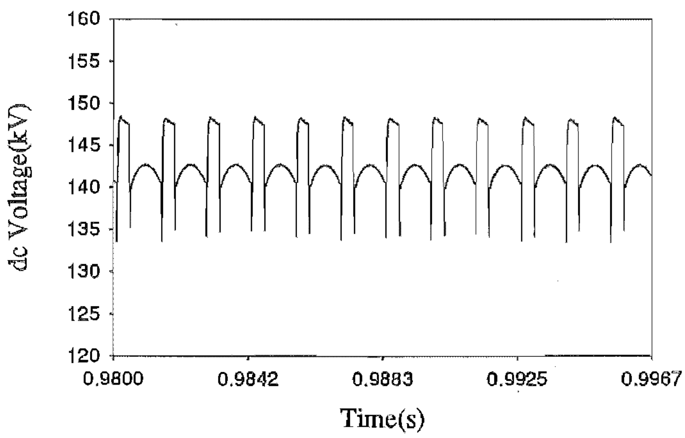
Figure 5.6 Steady state dc voltage waveforms: EMTDC 50 μs



(a) Rectifier end



(b) Inverter end



(c) Mid point

Figure 5.7 Steady state dc voltage waveforms: EMTDC 10 μs

5.5 Transient Performances

Transient simulation is a necessary tool for the studies aimed at understanding the influence of various control strategies on the system performance. Thus the validity of the digital simulation tools to simulate such transient conditions and control strategies must be established. Three test systems were used to present various transient responses of the hybrid algorithm which are compared with the corresponding conventional EMTDC responses.

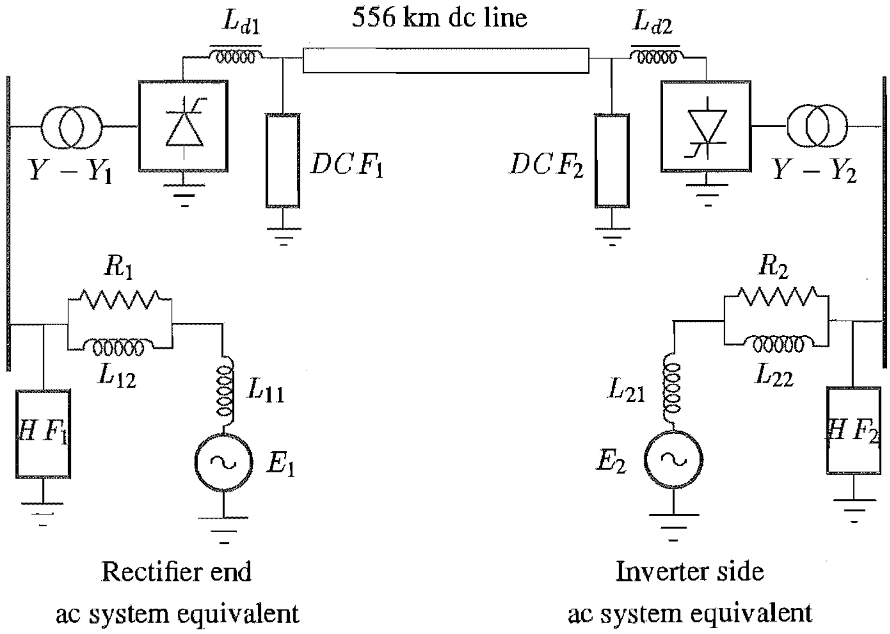


Figure 5.8 Test system 2 & 3; point-to-point dc link

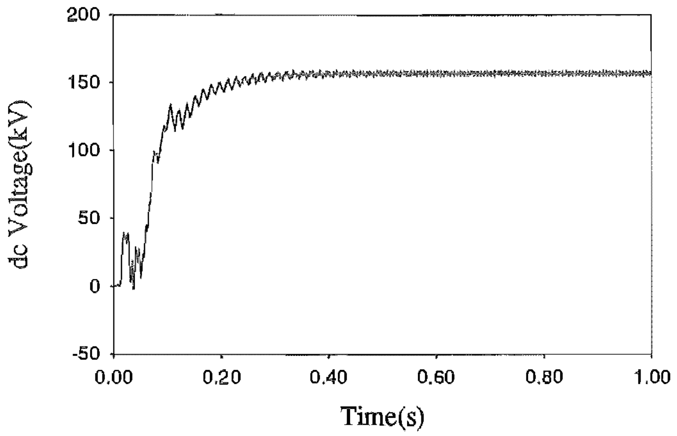
5.5.1 Test system 2

A point-to-point system as shown in Figure 5.8 was used in this case. The dc line was represented by the distributed parameter model and the relevant data are given in Appendix 5B. A simple controller with rectifier on CCC and inverter on EAC was used.

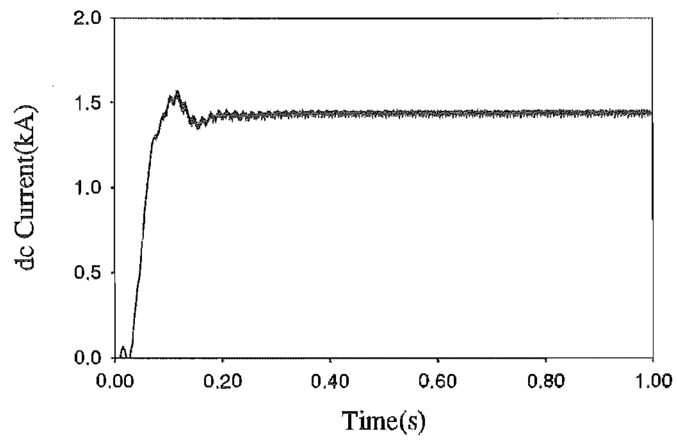
5.5.1.1 Hybrid Simulations

The system tearing required for the hybrid simulation was carried out as shown in Figure 4.3, with the ideal interfacing criteria. Similar to the back-to-back case the ac side interface is at the converter busbars but in this case an additional dc side interface is required to connect the distributed transmission line model as the dc line within the EMTDC network.

The system was started from an unenergized state by ramping up the ac voltage sources in 0.1 s. The start up responses of the inverter end dc voltage and the rectifier dc current are shown in Figure 5.9.



(a) Inverter end dc voltage



(b)Rectifier dc current

Figure 5.9 Test system 2 start up responses: Hybrid method

At 1.0 s the system was in absolute steady state conditions. To assess the accuracy of the hybrid model to simulate the system disturbances and taking into consideration the phase advance limitation during unsymmetrical conditions, a single phase fault of five cycles duration was applied to the inverter side of the link, which reduced the ac voltage by 70 %. The resulting waveforms for the inverter dc voltage and the rectifier dc current are shown in Figure 5.10.

5.5.1.2 EMTDC Simulations

The same system as above was simulated in EMTDC with a unified converter model, representation, and the dc line represented by its distributed parameter dc line model. The unified model represents the converter transformer, valves and their snubber circuits physically within the network, thus avoiding the necessity for a subsystem division. However, the presence of the

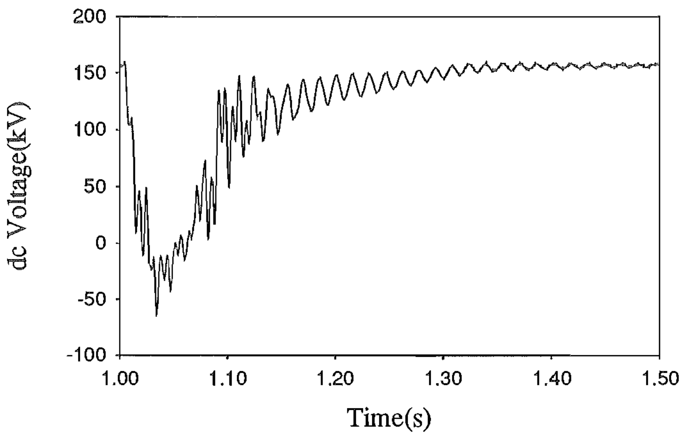
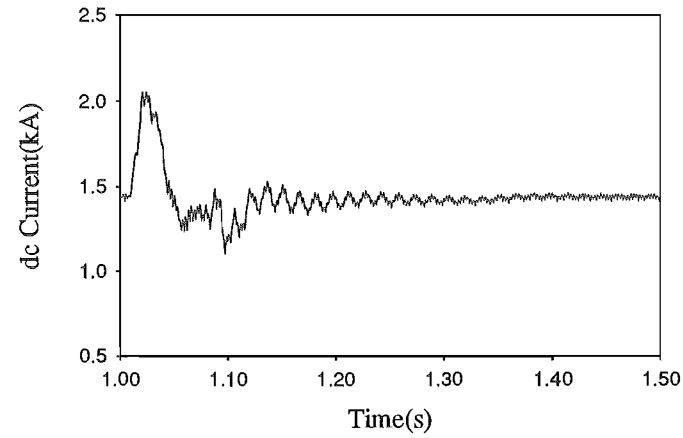


Figure 5.10(a) Inverter end dc voltage



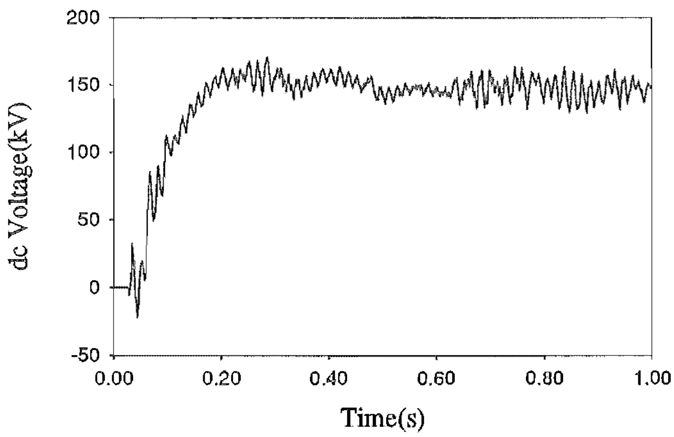
(b) Rectifier dc current

Figure 5.10 Test system 2 response due to a single phase 5 cycles fault at inverter end, Hybrid method

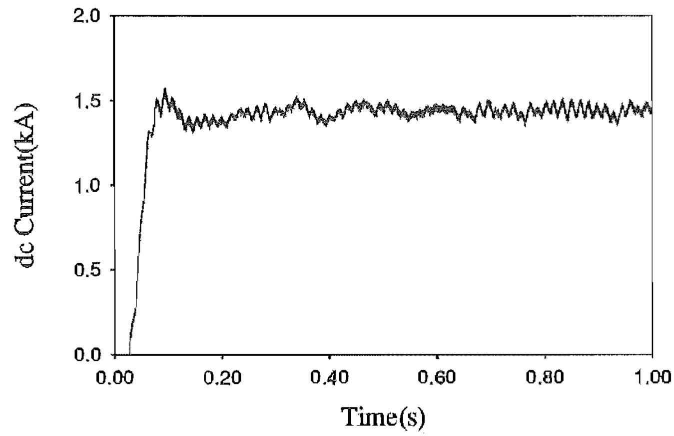
distributed parameter dc line model effectively isolates the two converters and their associated systems by dividing them into subsystems on the dc side. Both the rectifier and inverter end subsystems, therefore, include the ac system equivalents, the harmonic filters, converter transformers and the Graetz bridges. Interfaces in this case are handled implicitly by the distributed line model.

Several trials were run to identify the accurate response and the required step width for correct solution, by altering the step width. Initially a 50 μs step was used and the system was started with a 0.1 s ramp of the ac voltage sources, but a perfect steady state condition could not be achieved. The start up waveforms of the inverter dc voltage and rectifier dc current are shown in Figure 5.11. As explained earlier a reduced time step should locate the switching instants closely and avoid possible numerical oscillations to give a better response. The use of a 10 μs time step produced very stable responses as shown in Figure 5.12.

The same asymmetrical fault as applied to the hybrid case was simulated using the EMTDC



(a) Inverter end dc voltage



(b) Rectifier dc current

Figure 5.11 Start up response: EMTDC 50 μs

program, ie. reducing the phase A voltage by 70 % at the inverter terminals for five cycles.

In order to improve the system behaviour and locate a suitable step width, the time steps were progressively reduced in steps of 10 μs. When using a 40 μs step, the resulting fault response waveforms for the inverter dc current and the rectifier dc voltage, illustrated in Figure 5.13, although better than the 50 μs case, still shows incomplete recovery. Hence further step width reductions were attempted.

The response of the system to 30 μs and 20 μs steps are illustrated in Figures 5.14 and 5.15 respectively. The recoveries in these cases show considerable improvement from the previous cases. However, there are still differences in the dc current and voltage responses around 1.1 s and oscillations around 1.37 s, indicating that the solution is not perfectly stable.

Finally, a 10 μs step width was used and the responses are shown in Figure 5.16. This by far produced the best performances for the EMTDC solution which compares very well with the

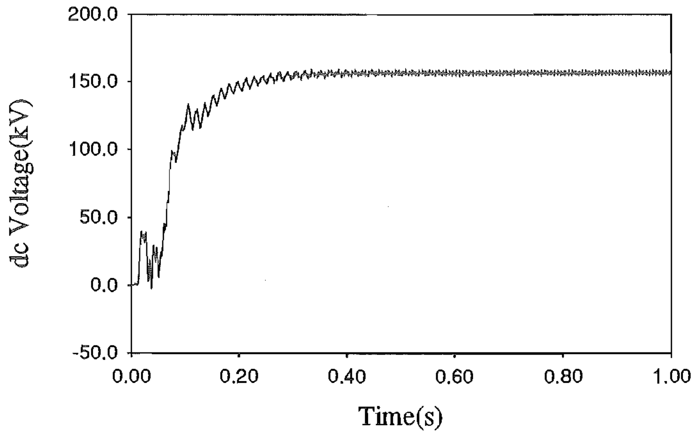
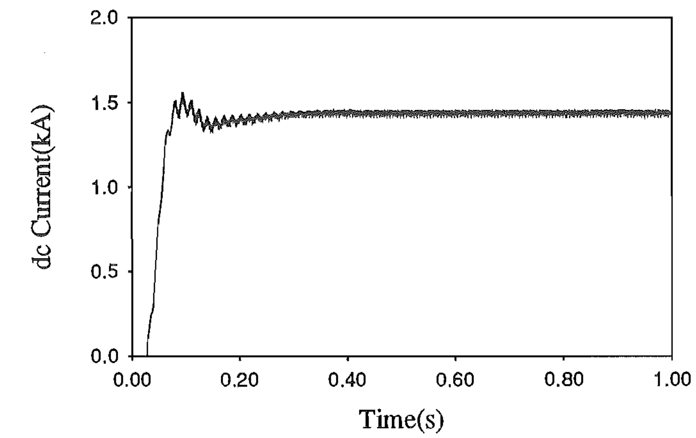


Figure 5.12(a) Inverter end dc voltage

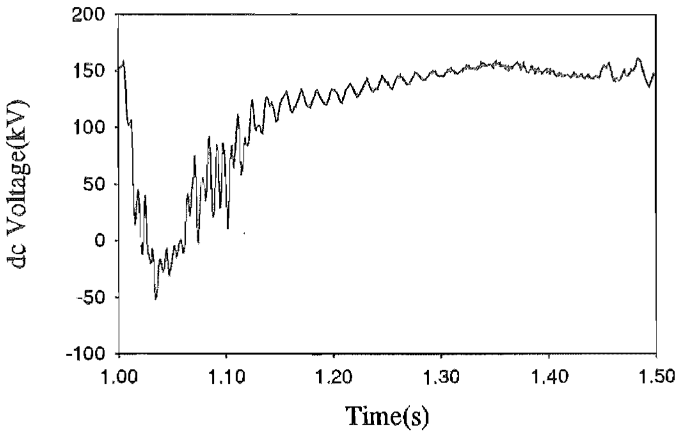


(b) Rectifier dc current

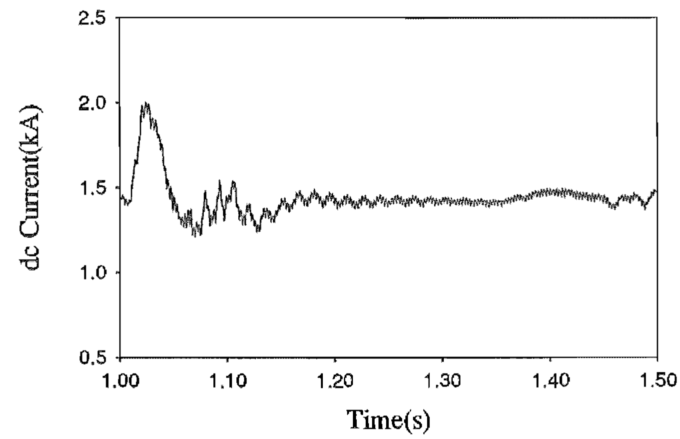
Figure 5.12 Start up response: EMTDC 10 μs

hybrid responses of Figure 5.10; but the latter were obtained using a 50 μs main program step. It can be seen that out of all the EMTDC responses, immediately after fault removal (around 1.1 s), only the 10 μs case has significant similarity with the hybrid solution, which also is totally free from numerical oscillations.

A smaller time step width of the EMTDC solution reduces the errors involved in the phase advancing method, and the unified solution avoids delays associated with interfacing. Also the switching instants fall closer to the time step boundaries reducing the possibilities of numerical oscillations. The 10 μs case closely satisfies all this criteria and can be taken as a realistic response. The hybrid simulation, on the other hand, produces the stable responses with a 50 μs time step with the inherent assumptions of phase advance being used. However, the inaccuracy in the assumption of balanced system is not considerable in this case and the hybrid solution method produces excellent numerical stability.



(a) Inverter end dc voltage



(b) Rectifier dc current

Figure 5.13 Test system 2 response due to a single phase 5 cycles fault at inverter end, EMTDC 40 μs

5.5.1.3 Simulation Performances

A comparison of the simulation times were carried out for this case on a VAX 3100 computer. The CPU times taken to simulate the system starting from unenergized state to steady-state up to 1.0 s is shown in Table 5.1 for the hybrid using 50 μs and the EMTDC using different step widths.

It will be shown later that the CPU time for the hybrid case will improve considerably with the extension of the ac system representation, as most of the computational time is spent on solving the switching devices. On the other hand the smaller step required by the EMTDC simulation will require a very large overhead. In this case a step width larger than 20 μs was needed for the EMTDC case to provide a more economic solution than the hybrid. However, as can be seen from the simulation results for the EMTDC cases such step could not guarantee an accurate or stable solution. Significant differences can be found in the dc voltage and current waveforms around 1.1 s

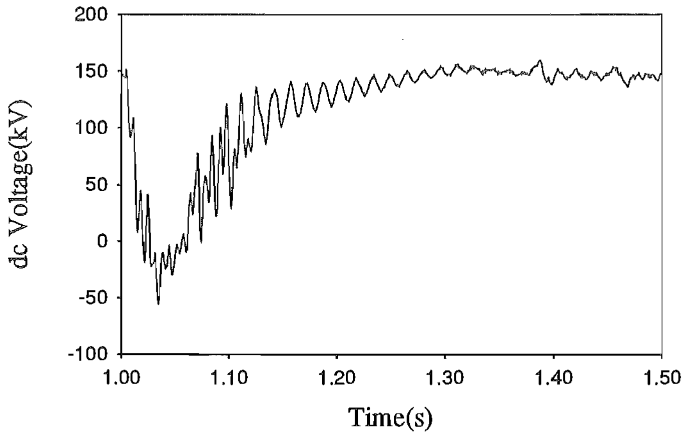
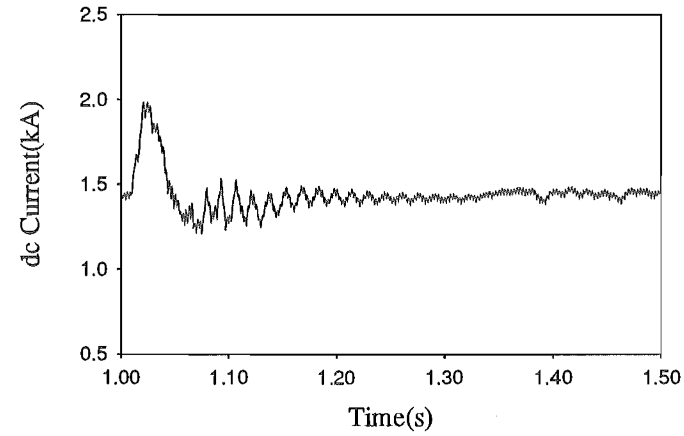


Figure 5.14(a) Inverter end dc voltage

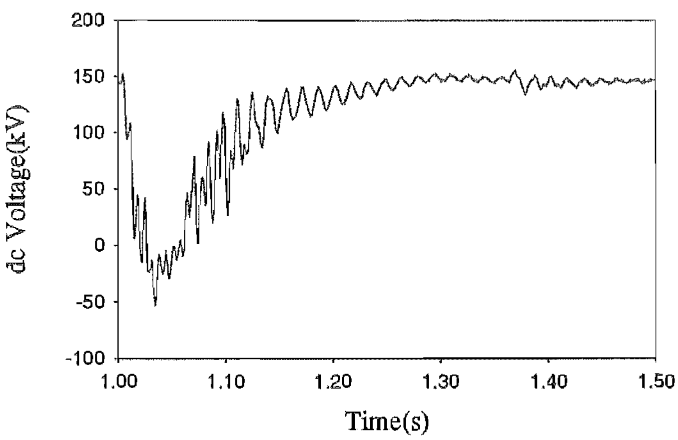


(b) Rectifier dc current

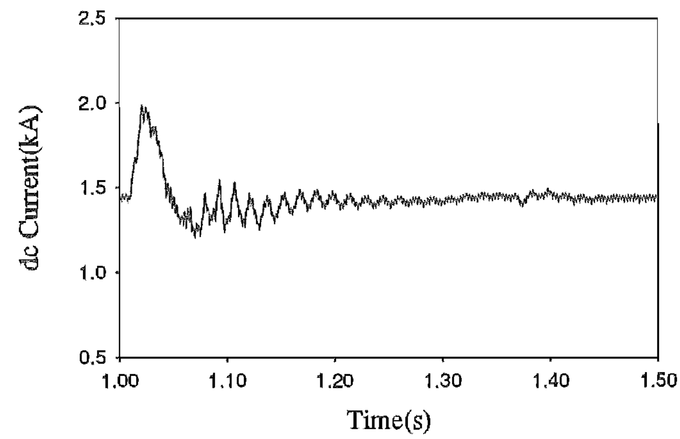
Figure 5.14 Test system 2 response due to a single phase 5 cycles fault at inverter end, EMTDC 30 μs

Case	CPU time(s)
EMTDC 50 μs	316
" 40 μs	378
" 30 μs	483
" 20 μs	692
" 10 μs	1379
Hybrid 50 μs	669

Table 5.1 Simulation performance times at different step sizes; Test system 2



(a) Inverter end dc voltage

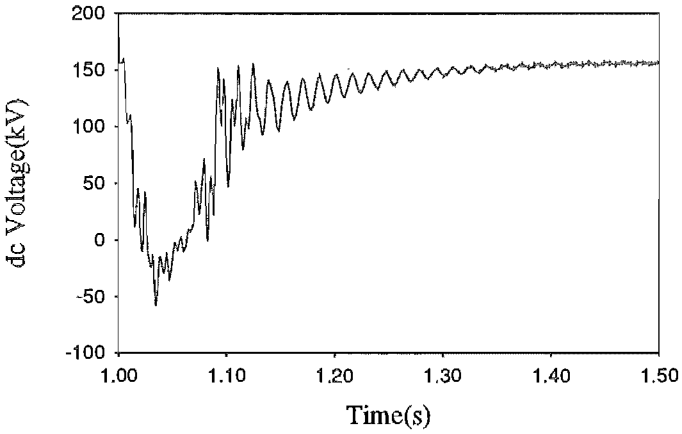


(b) Rectifier dc current

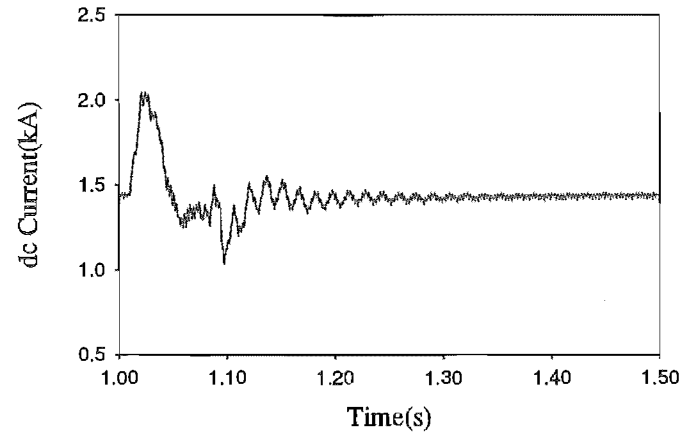
Figure 5.15 Test system 2 response due to a single phase 5 cycles fault at inverter end, EMTDC 20 μs

and 1.4 s. There are other ways to improve the stability of the solution, which require search for the solution with various numerical parameter modifications such as the valve resistances (R_{Von}) and damping parameters (R_d, C_d) or temporarily modifying the integration method [Alvarado *et al.*, 1983; Kruger and Lasserter, 1986a; Marti and Lin, 1989].

As explained in section 5.4.2, reducing the time step is not always necessary but this often shows a quicker way to locate the stable responses. The results compared in Table 5.1 were obtained with an ON state resistance of R_{Von}=0.05 Ω, damping resistance of R_d=1460.0 Ω and damping circuit capacitance of C_d=0.0867 μF, were used. Another set of values for the above parameters (R_{Von}=0.01 Ω, R_d=5000.0 Ω and C_d=0.05 μF) were able to reproduce the stable results even with a 50 μs step width resulting in twice as fast a solution than the hybrid method. This indicates that EMTDC can still produce good results at the hand of an experienced user. However, the uncertainty of the amount of acceptable damping needed to reproduce the real



(a) Inverter end dc voltage



(b) Rectifier dc current

Figure 5.16 Test system 2 response due to a single phase 5 cycles fault at inverter end, EMTDC 10 μs

system responses is a challenge particularly when there is no cross check available, because of the nature of the transient simulations where each state depends on the previous states of the system. Therefore any additional damping or any numerical oscillations from the present state may be carried forward to lead to an unacceptable result. Care is always needed in judging the responses as the inherent oscillations of the system may be damped out greatly due to the artificial damping introduced to curb the numerical oscillations. Moreover, it may result in considerable increase in valve damping circuit losses.

5.5.2 Test system 3

The differences with respect to Test system 2 are in the transmission line model, which now uses a five-pi sections lumped parameter representation, and in the control representation, which is explained in the next section. The steady state operating conditions are maintained the same as above. This test system was subjected to two fault conditions, a symmetrical and an asymmetrical ac faults.

5.5.2.1 Control System Representation

The power controller was represented in detail as shown in Figure 5.17(a). Power regulation is carried out by measuring the dc voltages and currents, and processing them sequentially through the blocks as indicated in the diagram. The measured inverter dc voltage is added to the dc transmission line resistive drop to give the compounded dc voltage, V_{comp} at the rectifier end, the lower value of which is limited to V_{min}. The set power order P_{order} divided by V_{comp} gives the desired current order. This desired current order is filtered, limited and then passed to the voltage dependent current order limiters (VDCOL) for the rectifier and inverter. The resulting individual current orders are processed by the respective pole current controllers and the valve group controllers to yield the final firing angle orders. A current margin of 0.1 p.u. was used for the inverter current controller and an 18 degrees minimum extinction angle was set to the inverter valve group controller. The DELAY in the diagram indicate the telecommunication delays, POLPI5 indicate the pole controller and the VG6P18 the valve group controllers. The measured gamma values are used as feedback variables for the VG6P18.

A sudden voltage decrease in the inverter ac system may lead to commutation failures, causing collapses of inverter dc voltage and a current overshoot followed by a phase back in the rectifier current controller [Wess *et al.*, 1991]. It is common practice to reduce the current reference at the rectifier when the dc voltage is depressed by the inverter side. This is the function of the VDCOL.

The VDCOL once activated is characterized by an unavoidable delay due to the ramping up process, the speed of which can be selected slow enough to avoid the occurrence of post-fault commutation failures. The VDCOL characteristic used is illustrated in Figure 5.17(b). For the VDCOL operation, recovery delays of 60 and 30 ms, and recovery ramp rates of 10 and 5 p.u./s were used for the rectifier and the inverter respectively.

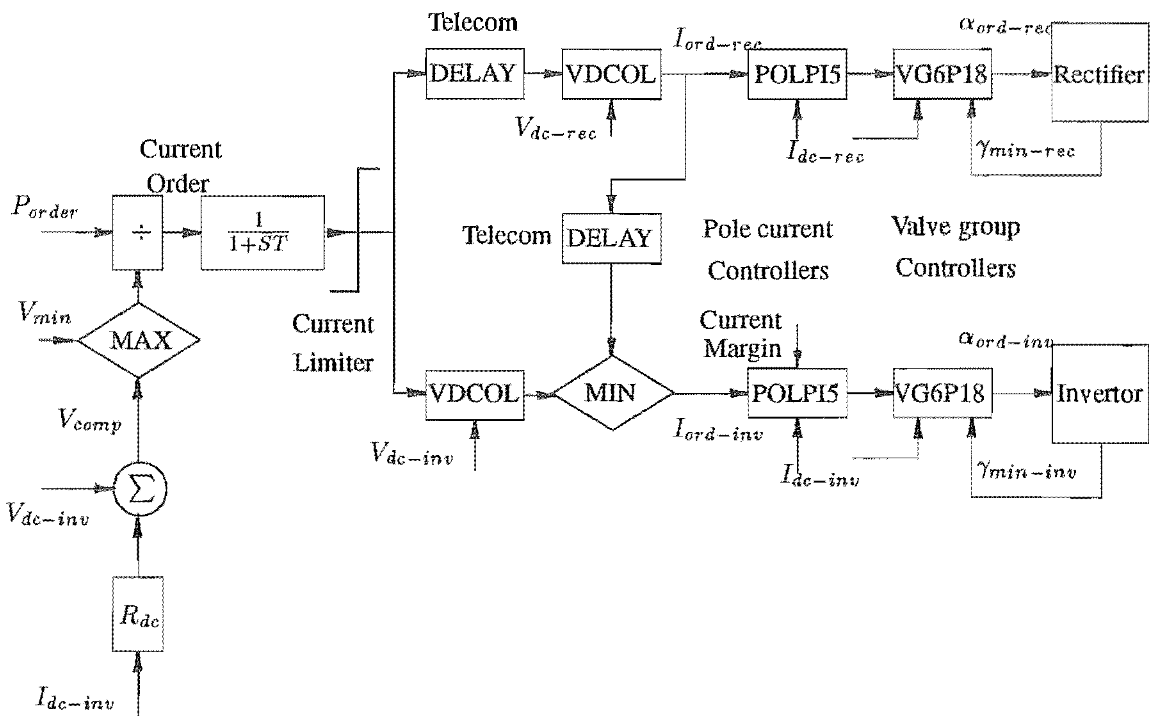
A power order of 255 MW at a dc voltage of 175 kV was set at the rectifier end with a V_{min} level of 140 kV.

In the following illustrations of Figures 5.19–5.24, the two vertical lines drawn at 1.0014 s and 1.085 s mark the fault application and removal times respectively.

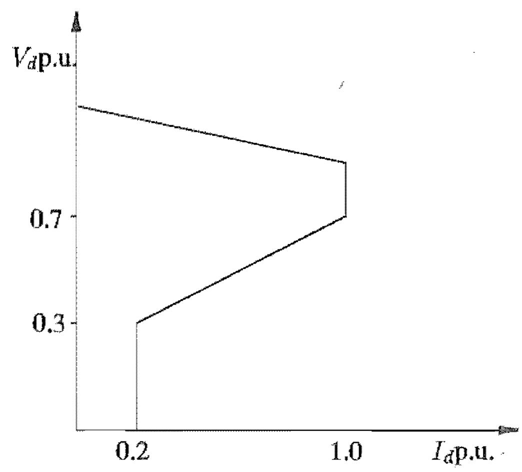
5.5.2.2 Hybrid simulation

For the hybrid simulations the dc system was modelled as part of the state variable representation. The pi section model of the dc line enables the complete dc system to be lumped together to form a continuous state variable based subsystem, including the rectifier, the dc line and the inverter. The subsystem tearing and interface were carried out as for Test system 1 case, ie. on the ac side.

A 50 μs step was used for the main program and as the maximum step width of the state variable solution. The system was started up by ramping up the ac voltage source in 0.1 s. Initially



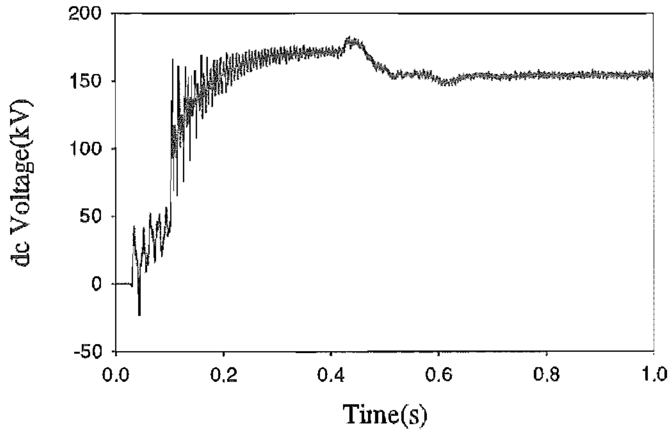
(a) Detailed Master Power Controller representation



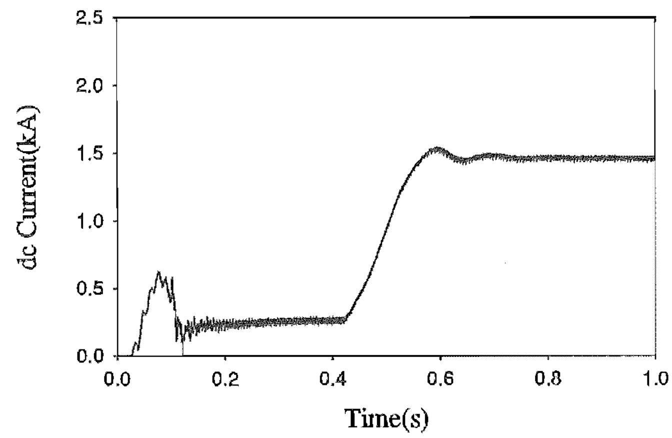
(b) Voltage dependent current order limiter (VDCOL) characteristic

Figure 5.17 Control system representation for Test system 2 the power order was set to 10 per cent of full load, at 0.4 s full power level was ordered and at 1.0 s the solution was assumed to have reached a steady state.

The start up responses, of the dc voltage at the inverter end and the rectifier dc current, are shown in Figure 5.18.



(a) Inverter end dc voltage



(b) Rectifier dc current

Figure 5.18 Test system 3 start up response: Hybrid method

Asymmetrical fault simulation: An ac short circuit was applied at the inverter ac side on phase A by reducing the equivalent emf source voltage to zero for 5 cycles. The resulting transient responses are shown in Figures 5.19 and 5.20. Figure 5.19 shows the inverter end dc voltage, rectifier dc current and the commutating voltage of faulted phase waveforms. The control variables $I_{ord-rec}$, $I_{ord-inv}$ are shown in Figure 5.20(a) and the compounded voltage V_{comp} is shown in Figure 5.20(b).

The system recovers from the fault smoothly. During the fault and recovery periods the effect of the VDCOL operation can be noted clearly with the different ramp rates and recovery delays as specified.

Symmetrical fault simulation: A symmetrical fault reducing the ac voltages by 90 % was applied to the inverter side for 5 cycles. The resulting responses for the inverter dc voltages and the rectifier dc currents are shown in Figure 5.21(a) and (b). Figure 5.21(c) shows the inverter end commutating ac voltages during the transient period. A similar recovery pattern to the asymmetrical fault case takes place owing to the VDCOL action, which reduces the current order during the fault period when the voltage drop was sensed and, upon fault clearance, holds it with the set delay after the voltage recovered, and ramps it up to the full load.

5.5.2.3 EMTDC Simulations

The EMTDC system was set up using the conventional converter modules and with three subsystems for the rectifier, the inverter and the dc system with the transmission line represented by five-pi sections.

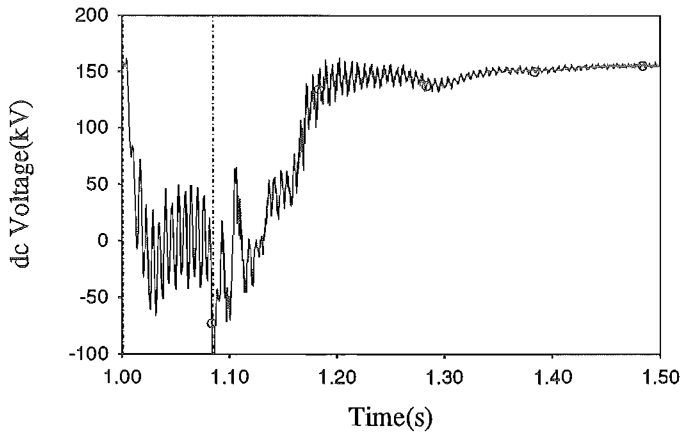
Asymmetrical and symmetrical fault simulations: The same fault conditions as for the hybrid simulation were used for the conventional EMTDC method and the resulting waveforms are shown in Figures 5.22 and 5.23 for the case of the asymmetrical fault and in Figure 5.24 for the symmetrical fault. The responses follow the same pattern as for the hybrid solution as shown above.

These cases indicate that the hybrid method produces similar responses to the EMTDC solutions. However, the EMTDC solutions required a judicious selection of the snubber circuit parameters and adjusting the step width to produce the same accuracy of the solutions. On the other hand, the hybrid algorithm is shown to perform properly without the need to search for the correct and stable solution as pointed out in section 5.5.1. It is also shown that the control system responses are identical in all cases presented. No effort has been made to optimize the control system parameters to improve the overall performance of the test system.

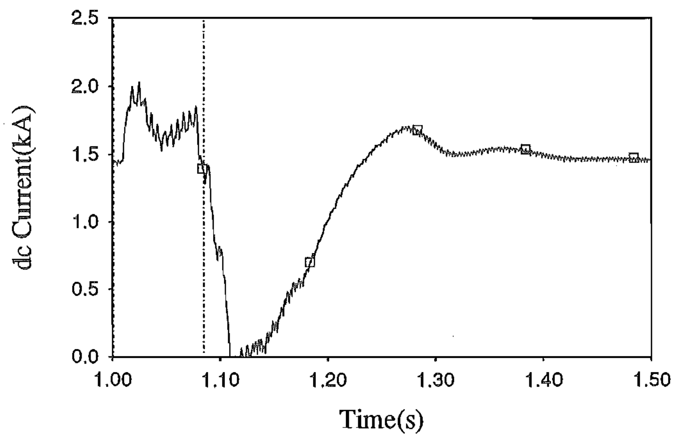
5.5.3 Test system 4

Realistic transient simulation studies of integrated ac/dc systems with disturbances at or close by the converter terminals can only be carried out if a fully detailed representation model for HVDC links is used. This is normally implemented with the existing simulation tools, but with the ac system represented by a Thevenin equivalent. However, the use of a fixed Thevenin equivalent for the ac system provides unrealistic levels of current and voltage [Giannakopoulos *et al.*, 1988b]. Therefore the ac system representation needs to be extended further away from the converter terminals to closely model the response of the actual system behaviour.

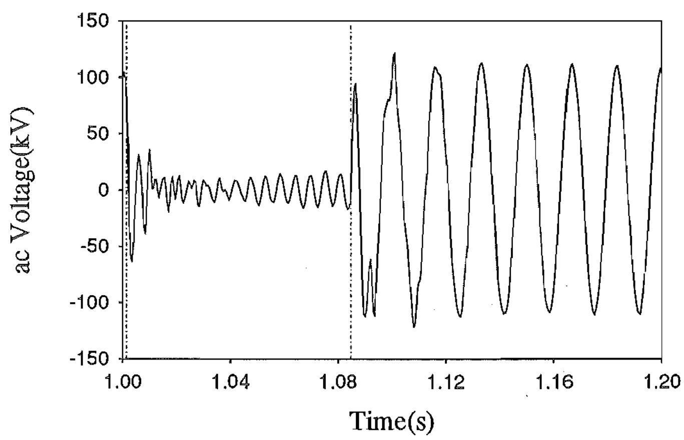
In order to model such a system Test system 4 was built using the back-to-back dc link of Test system 1 with the rectifier side being expanded further away from the converter bus as shown in Figure 5.25. Two remote generator equivalents Gen_1 and Gen_2 were placed at Bus_1 and



(a) Inverter end dc voltage

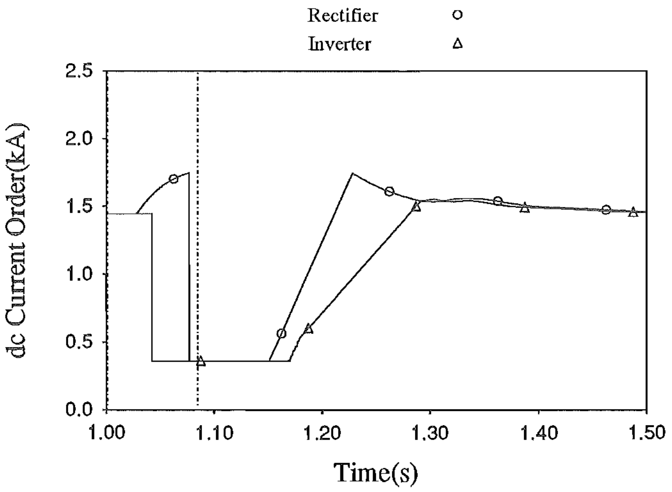


(b) Rectifier dc current

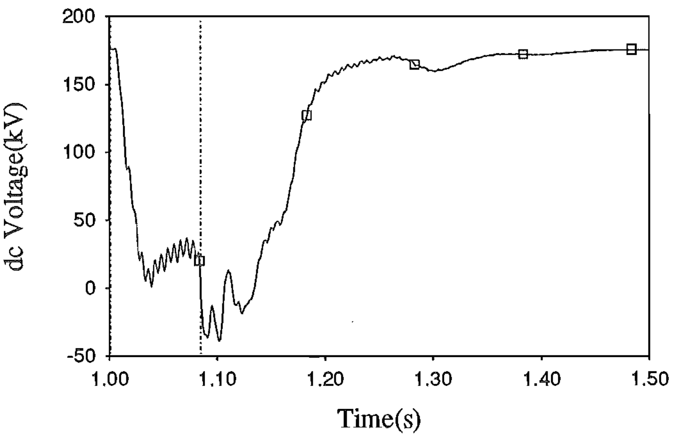


(c) Inverter end phase A voltage

Figure 5.19 Test system 3 transient response due to a single phase fault at inverter end: Hybrid method



(a) Final dc current order, $I_{ord-rec}$, $I_{ord-inv}$



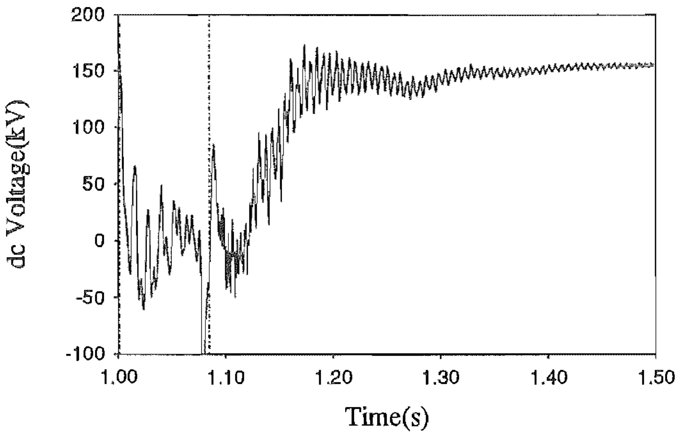
(b) Compounded dc voltage from inverter to rectifier, V_{comp}

Figure 5.20 Test system 3 transient response due to a single phase fault at inverter end: Hybrid method

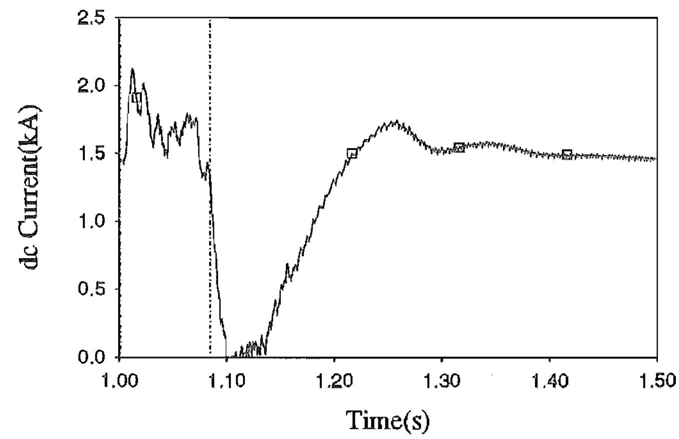
Bus_2 respectively. Two ac loads of 135 MW, 36 MVAr and 90 MW, 54 MVAr were connected to Bus_3 and Bus_2 respectively. The transmission lines were all represented by EMTDC distributed parameter line models. The rest of the system, from the ac harmonic filter at the rectifier end to the back-to-back and the inverter side ac system equivalent, including the control systems, are all similar to that of Test system 1. The control system responses were not optimized, but exactly the same control system was used for both cases. The presence of transmission lines effectively separate the ac system into three disconnected subsystems.

Keeping all the valve groups blocked initially the system was started by ramping up the ac voltage sources in 0.28 s. The inverter was deblocked after 0.05 s and the the rectifier after 0.12 s. The start up responses of the mid-point dc voltage and dc current for the hybrid method are shown in Figure 5.26.

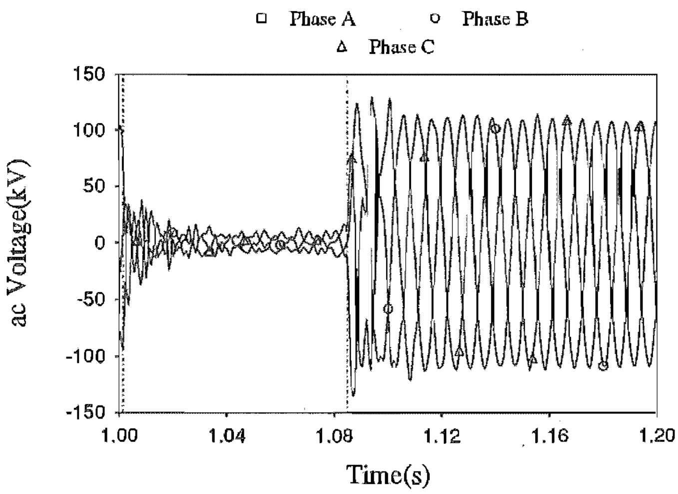
A single phase fault of five cycles duration was applied at 1.0 s (from 1.0 s to 1.0833 s) to



(a) Inverter end dc voltage

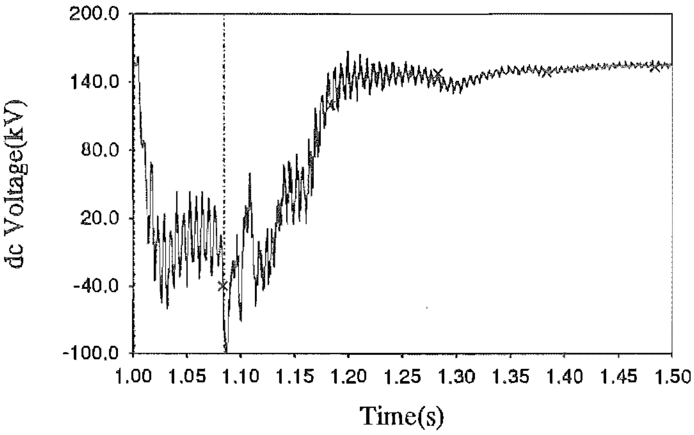


(b) Rectifier dc current

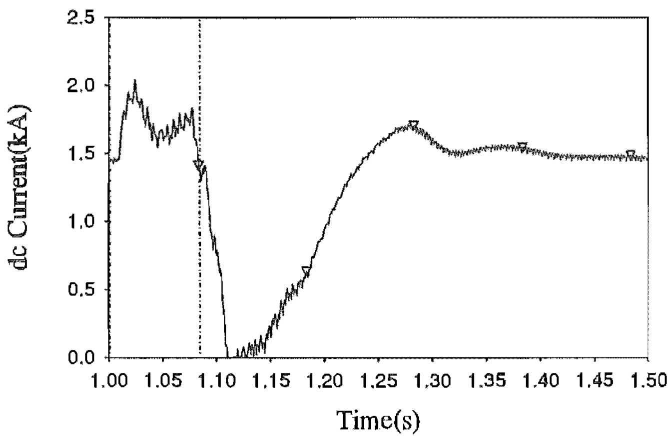


(c) Inverter end ac bus voltage

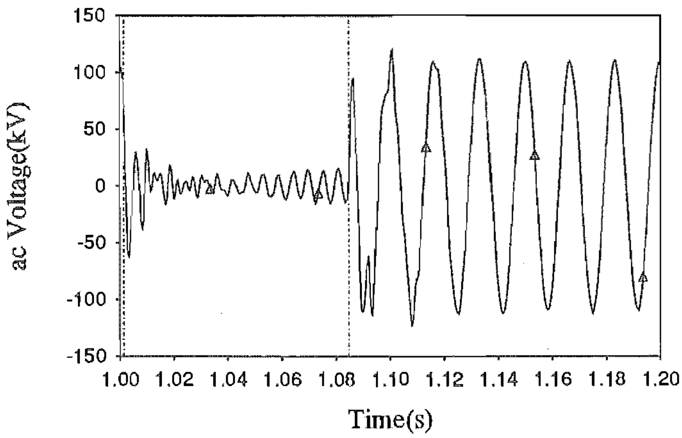
Figure 5.21 Test system 3 transient response due to a three phase fault at inverter end: Hybrid method



(a) Inverter end dc voltage

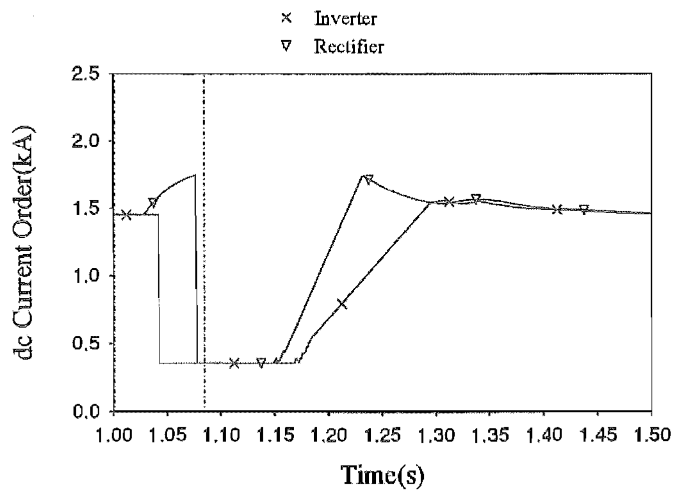


(b) Rectifier dc current

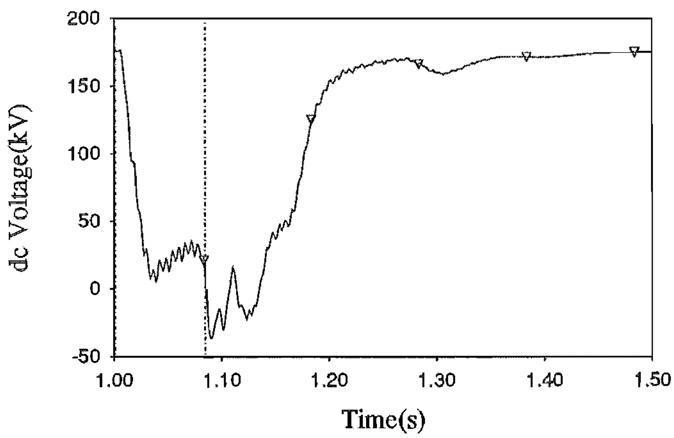


(c) Inverter end phase A voltage

Figure 5.22 Test system 3 transient response due to a single phase fault at inverter end: EMTDC



(a) Final dc current order $I_{ord-rec}$, $I_{ord-inv}$



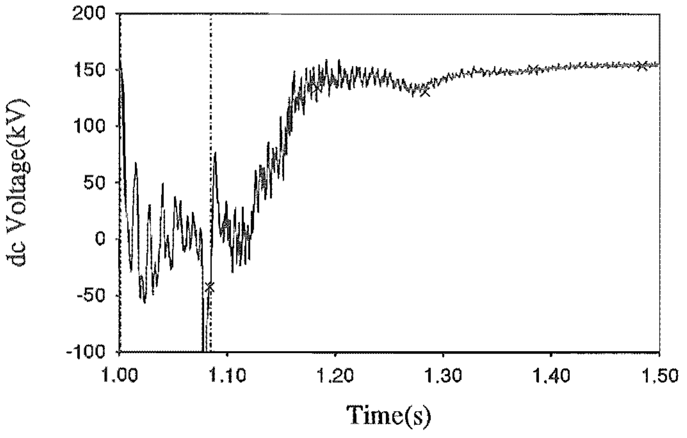
(b) Compounded dc voltage from inverter to rectifier

Figure 5.23 Test system 3 transient response due to a single phase fault at inverter end: EMTDC

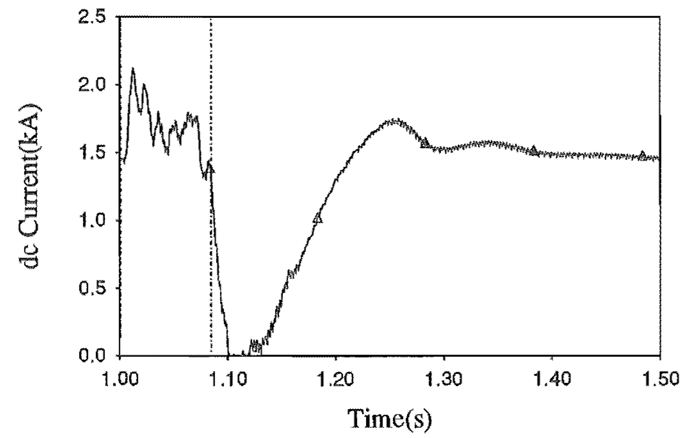
Gen_1 which reduced the phase A voltage by 30 %.

5.5.3.1 Hybrid simulation

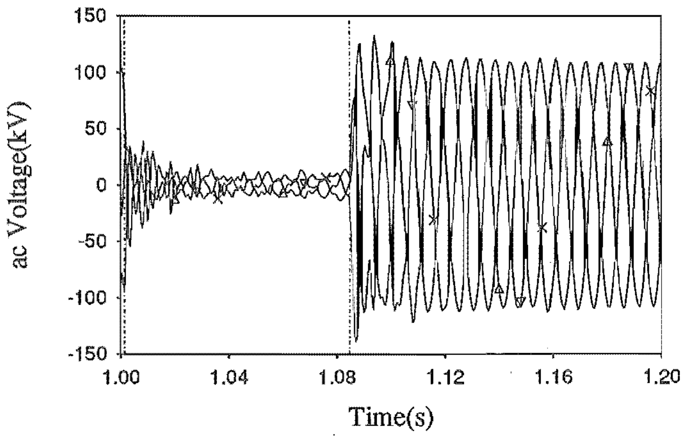
Interfacing the power network was carried out as for Test system 1 and a 50 μs step width was also used for the hybrid solution. Complete transient responses of the mid point dc voltage and the dc current during the fault and recovery period are shown in Figure 5.27 and the mid point dc voltage waveform is expanded for closer examination in Figure 5.28(a). The CPU time required for 1.0 s simulation was 413 seconds.



(a) Inverter end dc voltage



(b) Rectifier dc current



(c) Inverter end ac bus voltage

Figure 5.24 Test system 3 transient response due to a three phase fault at inverter end: EMTDC

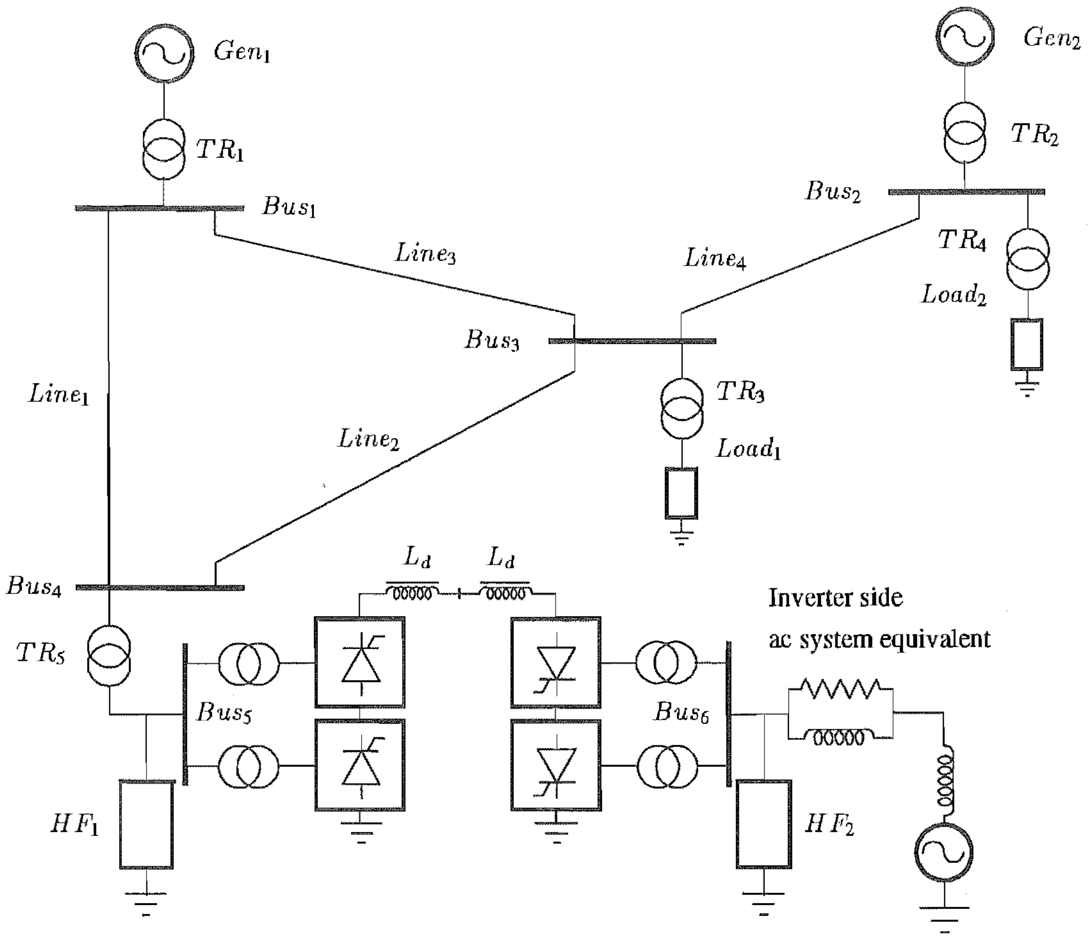
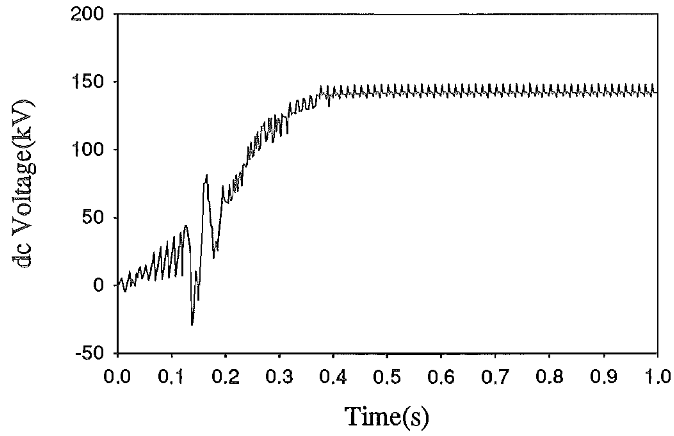


Figure 5.25 Test system 4; back-to-back dc link with extended ac system

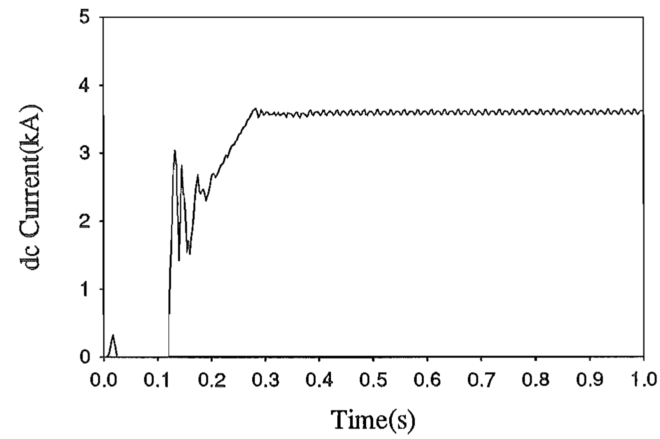
5.5.3.2 EMTDC simulation

The back-to-back system was represented by the conventional converter modules and 50 μs step width was used to simulate the same asymmetrical fault condition. As for the hybrid case, a single phase fault of five cycles was applied to Gen_1. The responses were quite different to the hybrid solution, particularly during the fault period, as can be seen from the expanded mid point dc voltage waveform during the fault period, shown in Figure 5.28(b). Considerable differences are observed between Figure 5.28(a) and Figure 5.28(b), eg. the sharp drop in voltage at 1.03 s and the post fault recovery voltage around 1.1 s. In this case the CPU time for 1.0 s simulation was 243 seconds.

In order to verify the responses of the hybrid and the EMTDC solution, a 10 μs step width case was simulated. The corresponding fault period response is shown in Figure 5.28(c) shows close agreement with the hybrid response of Figure 5.28(a) expanded during the fault period. The required CPU time increased to 1216 seconds. Although, it is possible to change the response using different combinations of the additional parameters, the choice of an acceptable combination is left to the users judgement when prior knowledge of the system under test is not available.



(a) Mid point dc voltage



(b) dc current

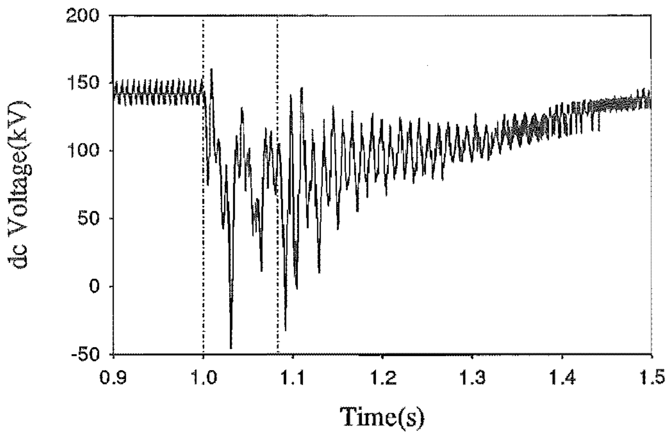
Figure 5.26 Test system 4 start up response: Hybrid method

5.6 Validation of the Hybrid Solution

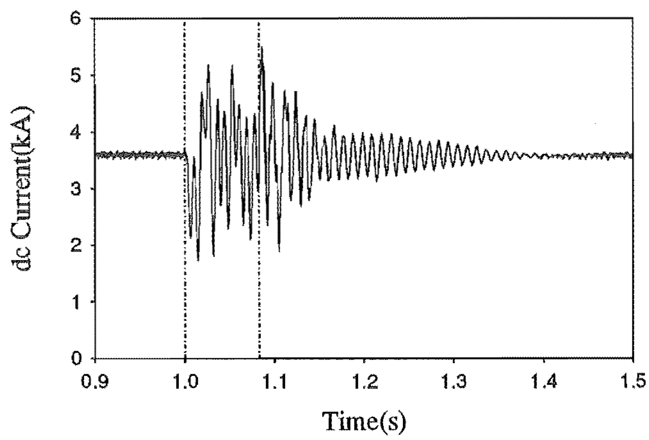
The responses of the conventional EMTDC and the hybrid solutions have been illustrated in four test systems. The outstanding features of the hybrid solution method have been identified in the four cases.

Test system 1 has shown the stable and accurate performance of the hybrid solution method in its steady state waveform reproductions. The responses are repeatable and stable without the presence of spurious spikes or any numerical oscillations. With the EMTDC program a similar performance required a substantial increase in CPU time.

Test system 2 has shown the effect of the step width on the transient response solution. A 50 μs to 10 μs step reduction in the EMTDC solution has shown a significant change in system response which gets very close to the predicted results of the hybrid solution, while a 50 μs step



(a) Mid point dc voltage



(b) dc current

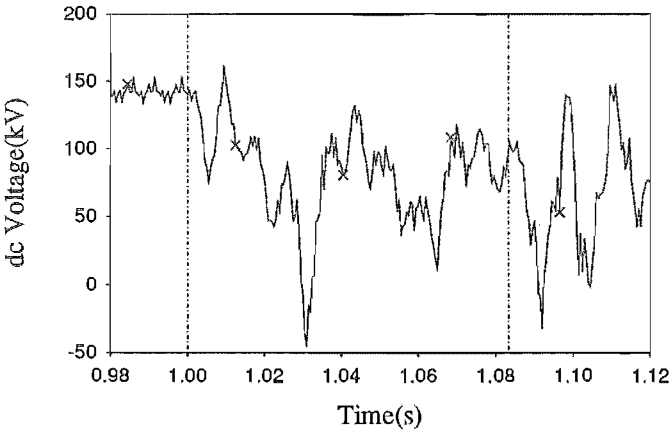
Figure 5.27 Transient response due to a remote fault at Gen_1: Hybrid method

was adequate for the hybrid solution to achieve the same accuracy.

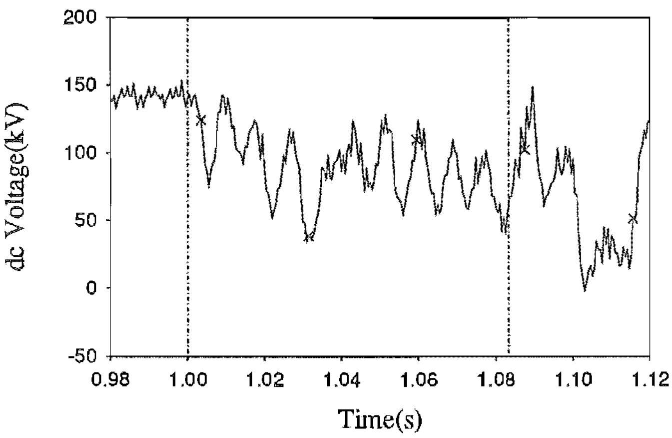
A practical ac/dc system needs extensive control system representation as shown in the third test system case of Test system 3. The hybrid responses compared against the EMTDC solutions showed excellent agreement, highlighting the accuracy of control system and the overall system representations.

Test system 4 showed how a realistic ac/dc system can be represented with the hybrid algorithm and the resulting performance improvement over the conventional EMTDC algorithm.

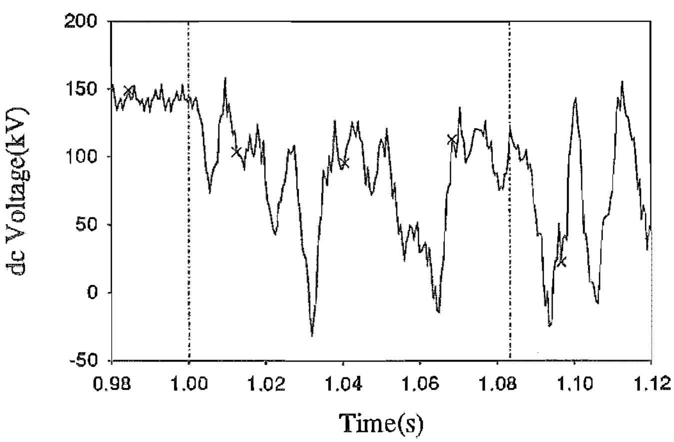
These simulations demonstrate most of the features which would be expected in realistic ac/dc power systems. It has also been shown how it is possible to include the other local non-linearities attached to HVdc converter plant.



(a) Hybrid method



(b) EMTDC 50 μs



(c) EMTDC 10 μs

Figure 5.28 Expanded dc voltage response at mid-point due to a remote fault at Gen_1

5.7 Conclusion

It has been shown that the hybrid solution method can produce very accurate transient simulations of HVdc power systems including the local non-linearities. The essence of the approach is in decoupling the systems requiring accurate detection of non-linearities and avoiding numerical oscillations with a stable numerical process. Accurate detection of switching instants not only improve the numerical stability of the solution, but also improves the waveform accuracies. Very stable transient performances are possible without the requirement for additional computation overhead. Considerable savings in computational time can be achieved with a realistic ac system representation.

Thus an economic and accurate simulation is possible with the hybrid simulation without the need for extra effort by the user to tune the system for its numerical performance, most importantly selecting the correct responses when there is no cross check available, either the real system response or from another simulation tool. The real advantage comes from the hybrid responses not having to search for the additional parameters for final results. These parameters are normally selected based on the considerations to avoid the numerical oscillations and in the hands of an experienced user EMTDC can produce good results. The acceptable value of added damping has to be judged according to the time step and the study of interest.

Appendix 5A Test system 1 data

Smoothing reactors	$L_d = 34.0\ mH$		
Convertor transformers			
TR1, TR2	315 kV/60 kV	305 MVA	18% leakage
TR3, TR4	120 kV/60 kV	305 MVA	18% leakage
a.c. system equivalents			
$R_1 = 13.1\ \Omega$	$L_{11} = 95.4\ mH$	$L_{12} = 22.2\ mH$	
$R_2 = 10.8\ \Omega$	$L_{21} = 21.0\ mH$	$L_{22} = 10.49\ mH$	
E_1	$340.48\ kV\ rms\ l-l$ 60 Hz		
E_2	$129.82\ kV\ rms\ l-l$ 60 Hz		
d.c. system rating	506 MW 3.6 kA		

Harmonic Filters				
Location	Order	$R\ (\Omega)$	$L\ (mH)$	$C\ (\mu F)$
Rectifier end	11^{th}	1.13	27.4	2.12
	13^{th}	0.25	19.5	2.12
	HP24	184.2	5.09	2.4
Invertor end	11^{th}	0.163	4.0	14.6
	13^{th}	0.14	2.85	14.6
	HP24	26.66	0.737	16.58

Appendix 5B Test system 2 data

Smoothing reactors	$L_d = 0.75\ H$		
Convertor transformers			
TR1	134 kV/134 kV	341 MVA	20% leakage
TR2	127 kV/127 kV	323 MVA	20% leakage
a.c. system equivalents			
$R_1 = 1.1261\ \Omega$	$L_{11} = 6.82\ mH$	$L_{12} = 2.43\ mH$	
$R_2 = 3.7732\ \Omega$	$L_{21} = 11.65\ mH$	$L_{22} = 7.28\ mH$	
E_1	$145.00\ kV\ rms\ l-l$ 60 Hz		
E_2	$126.27\ kV\ rms\ l-l$ 60 Hz		

Rectifier d.c. Current setting	1.44 kA
Inverter minimum extinction angle	18 degrees

Harmonic Filters				
Location	Order	$R\ (\Omega)$	$L\ (mH)$	$C\ (\mu F)$
Rectifier end	5^{th}	1.776	54.57.4	5.153
	7^{th}	2.6664	54.57.4	2.6294
	11^{th}	1.776	13.51	4.3204
	13^{th}	1.776	13.51	3.0929
	HP	184.2	1.29	12.373
Invertor end	5^{th}	2.1032	44.2	6.3522
	7^{th}	2.1032	44.2	3.2408
	11^{th}	0.7887	11.7	4.9828
	13^{th}	0.7887	11.7	3.5678
	HP	11.04	1.07	15.367

dc line data (distributed parameter model)	
Lower frequency	5.0 Hz
Higher frequency	60.0 Hz
Resistance at lower frequency	0.025 Ω/km
Resistance at higher frequency	0.03 Ω/km
Total line length	556 km
Mode travel time	3.037 ms
Surge impedance	300.0 Ω

Appendix 5C Test system 3 data

dc line data (five π sections)	
Capacitance per unit length	0.0182 $\mu F/km$
Inductance per unit length	1.64 mH/km
Resistance per unit length	0.025 Ω/km
Total line length	556 km

The rest of the data are similar to that of Test system 2.

Appendix 5D Test system 4 data

Convertor transformers, Smoothing reactors, inverter side ac system and ac harmonic filters are the same as for test system 1 but an extra capacitor (C = 1.942 μF) is added to Bus_5.

Gen_1		$14.49\ kV\ rms\ l-l$	$60\ Hz$
Gen_2		$11.55\ kV\ rms\ l-l$	$60\ Hz$
a.c. system Loads			
$Load_1$		$135 MW\ \ 36 MVAr$	
$Load_2$		$90 MW\ \ 54 MVAr$	
Transformers			
Unit	MVA	Ratio(kV/kV)	leakage(%)
TR1	600	315/220	9.4
TR2	600	220/13.8	9.6
TR3	150	220/33	4.8
TR4	110	220/11	20.0
TR5	250	220/11	20.0

All transformers take 0.5 % magnetizing current.

ac transmission line data:

```
3             / no. of conductors        (220 kv)
0             / number of ground wires   --------
 40.000       / steady state or lower frequency(Hz)
 1500.00      / higher transient frequency (Hz)
 length       / line length (m)
 100.00       / ground resistivity (ohm-m)
12.980-03     / conductor  1 radius (m)
1             / number of conductors in bundle 1.
 12.5         / conductor  1 height (m)
  4.05        / conductor  1 horiz. dist
0.09010-03    / conductor  1 dc res./l  (ohm/m)
12.980-03     / conductor  2 radius (m)
1             / number of conductors in bundle 2.
 19.2         / conductor  2 height (m)
  3.70        / conductor  2 horiz. dist
0.09010-03    / conductor  2 dc res./l  (ohm/m)
12.980-03     / conductor  3 radius (m)
1             / number of conductors in bundle 3.
 25.9         / conductor  3 height (m)
  3.55        / conductor  3 horiz. dist
0.09010-03    / conductor  3 dc res./l  (ohm/m)
```

where, the line lengths are:

	length
$line1, line4$:	17500
$line2, line3$:	8750

Chapter 6

GENERAL CONCLUSIONS AND FURTHER WORK

6.1 Conclusions

Thorough testing must be performed on HVdc transmission control and protection systems during the development stages and prior to commissioning. Generally, physical simulators operating in real time have been in use for decades. However, these suffer from limitations in their modelling capacity and, more often, from limited accessibility, owing to the high cost involved. A number of alternative digital solutions have emerged and at present sophisticated digital tools are available to power system engineers. A review of the many such digital simulation alternatives for HVdc system analysis had been presented in chapter 2, and an advanced state variable algorithm, TCS, considered in chapter 3.

The EMT programs have been universally accepted for general purpose transient simulation as they are capable of handling very large networks efficiently. Also an efficient representation of detailed transmission line modelling is possible. Although originally intended for ac transmission systems, EMT programs were subsequently extended to dc transmission studies. Their formulation is based on the trapezoidal integration method, which is stable as an integrator but suffers from numerical oscillations when required to function as a differentiator. Therefore, when the slope of a current flowing through an inductance changes sharply, numerical oscillation results in the voltage across the inductance. This also happens with the current through the capacitor when the slope of the voltage across changes suddenly. Many remedial techniques have been in use and are discussed in chapter 2.

The state variable based TCS program and in particular its strength in modelling switching and other non-linearities have been discussed in detail. The use of variable step length integration and the ability to change the solution accuracy for each run, permits the use of a large step until the system arrives at steady state. To improve the waveform resolution the step length could be reduced for a final short run. With this possibility TCS can be used to solve the converter network as a part of a Newton type iterative approach for harmonic analysis.

Apart from valve switching discontinuities, when power electronic and any other devices, such as transformers with magnetic saturation, are represented with their non-linear characteristics a reduced time step width may be necessary to accurately reproduce the behaviour of the device. This requirement is met by the automatic time step adjustment feature of TCS which reduces the time step around the knee region or where sharp changes in characteristics are noted, and takes large strides elsewhere (in the mostly linear or linearly extended part of the curve).

This thesis has identified the best features of the two major techniques used for transient simulations of HVdc/ac systems, the EMTP and state variable methods, and proposed a solution method based on a hybrid approach. Although attempts have already been made in this direction these have been restricted to the modelling of single power electronic components, such as a static VAr compensator and a single HVdc converter bridge. The present approach is of more general applicability and can model a complete HVdc system as a continuous system with arbitrary interconnection of network components and automatically generate the state equations.

In the implementation of the hybrid method presented in chapter 4, EMTDC functions as the main program while TCS solves the HVdc converters and the surrounding non-linearities. The hybrid solution performances are compared with the conventional EMTDC responses. In order to obtain similar steady-state and transient performances with both the hybrid and EMTDC algorithms the step length of the latter had to be reduced by about five times, resulting in a five times increase in CPU time. The hybrid solution runs with at least twice the speed and produces similar accuracy; moreover the efficiency of the hybrid solution increases with the size of the ac system representation. With the hybrid algorithm it is possible to simulate HVdc/ac transmission systems efficiently without the need for careful preconditioning.

At the point of interface between the EMTDC and TCS, sufficient capacitance and inductance must be present to ensure that stable voltage and current are exchanged across the interface. HVdc converters are ideally suited for interfacing as they possess stable commutating bus voltages and a smooth dc current. In the absence of such stable information for subsystem division the network has to be modelled as a continuous subsystem. For example in the case of a unit connected generator converter (without the harmonic filters), the converter and generator both should be represented in TCS as a continuous state variable based subsystem.

A new converter control option is incorporated as a part of the TCS solution according to the strategy used by EMTDC; it is implemented by modifying the basic converter firing control at a lower level in the model. This alternative has been particularly useful for the verification of the hybrid implementation with reference to EMTDC results.

6.2 Further work

When starting the simulation from uninitialized states the steady-state solutions are arrived at only after sufficient time has elapsed to ensure that the transients have decayed. The TCS program has a facility to initialize the network to load flow values. Although the true steady-state is reached only after a few cycles of simulation, this provides a reasonable estimate for the starting conditions. On the other hand the EMTDC program, at present, does not have a facility to completely initialize the system to its steady-state solution. Recently, Usaola and Mayordomo (1990) have shown the possibility of fast steady state initialization of a network, including non-linear elements, based on a Newton-Raphson iterative technique. This formulation is compatible with EMT programs. A similar method should be extended to provide steady-state solution for the hybrid implementation.

For simplicity the three phase transformer saturation characteristics are normally represented assuming single phase transformer banks without considering the magnetic cross coupling between phases. Detailed representations were avoided due to the unavailability of sufficient data and due to lack of accurate models. However, extensive studies have proved that such representations give pessimistic results [Medina and Arrillaga, 1991]. Therefore, a more accurate transformer representation needs to be implemented based on the model of the above reference.

The hybrid solution is particularly suited to systems with multiple non-linear power electronic devices such as proposed by the FACTS technology. In addition to the available HVdc component models, other component models specific to FACTS devices should be added to the TCS program for such applications.

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